A Holistic Investigation of Complexity Sources in Nuclear Power Plant Control Rooms

by

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A Holistic Investigation of Complexity Sources in Human Supervisory Control Domains

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Abstract

The nuclear power community in the United States is moving to modernize aging power plant control rooms as well as develop control rooms for new reactors. New generation control rooms, along with modernized control rooms, will rely more heavily on automation and computerized procedures. Of particular importance to the Nuclear Regulatory Commission (NRC) is the impact such modernizations or new technologies will have upon operator performance and reliability in these safety-critical control room environments. One specific area of interest is the effect that various complexities in the control room have on operator performance and reliability. This research identifies various definitions of complexity and characterizes complexity in the nuclear power plant (NPP) domain, focusing on the common complexity dimensions of number, variety, and interconnections. Based on this characterization of complexity, a comprehensive list of complexity sources within the NPP control room is presented, along with a novel approach to describe complexity source interconnections.

Understanding the sources of complexity in advanced NPP control rooms and the associated effects on human reliability is critical for ensuring safe performance of both operators and the entire system. However, most of the previous approaches in investigating complexity typically focus on either objective or subjective views of complexity, and a systematic approach that considers both views is missing from previous approaches. This research provides a novel methodology to assess the sources of complexity in NPP control rooms both objectively and subjectively while understanding the difference between the two and introduces a systems-theoretic descriptive model of these sources of complexity, leveraging network theory. Finally a method is introduced to investigate the differences between the complexity views of different groups of NPP stakeholders.

Incident report databases and in particular, 22 nuclear incidents in the Human Event Repository and Analysis (HERA) database were parsed to find objective evidence for the identified sources. Using this evidence-based approach, some of the potential interactions between these sources could be captured. A network called "Complexity Source Network" (CSN) was created for each incident in HERA to present the sources (nodes) and potential interactions between them (links). An ensemble of networks was developed consisting of 22 CSNs, one for each of the incidents in HERA. A tool called CXViz was developed to visualize and analyze the CSNs. Using the aggregate network (22 CSNs combined) the most common sources and interactions were identified. The complexity views of three groups of stakeholders, namely Operators, Designers and NRC Reviewers, were collected using a survey tool called CXSurvey. Using this tool, the interviewees were asked to rate the identified sources of perceived complexity and to rank the top five in terms of contribution to perceived complexity.

Data gathered from 16 operators, 8 designers and 3 NRC reviewers were collected and the top five sources identified by each group were compared to the top five most supported sources from the 22 incidents in HERA. The results show large variations between the subjective views of the operators and designers and the objective top five. In addition, the subjective source rating of the three groups of stakeholders were compared. The results show large variations between the complexity views between the stakeholders on some controversial sources such as boredom, and training.

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List of Acronyms

ATC	Air Traffic Control
BOP	Balance of Plant
CC	Clustering Coefficient
CPL	Characteristic Path Length
CSN	Complexity Source Network
CSNI	Committee on Safety of Nuclear Installations
HCI	Human-Computer Interaction
HERA	Human Event Repository and Analysis
HF	Human Factors
HFE	Human Factors Engineering
HFIS	Human Factors Information System
HRA	Human Reliability Analysis
HSC	Human Supervisory Control
HSI	Human-System Interface
ISO	Independent Systems Operator
LEF	Licensee Event Report
MIT	Massachusetts Institute of Technology
ND	Network Density
NEA	Nuclear Energy Agency
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission

NSSS	Nuclear Steam Supply System
OEM	Original Equipment Manufacturer
PORV	Pilot-operated Relief Valve
SME	Subject Matter Expert
STAMP	System-Theoretic Accident Modeling and Processes
TMI	Three Mile Island
TTC	Technical Training Center
V&V	Verification and Validation

1. Introduction

1.1 Motivation

The nuclear power industry in the United States has declined in terms of growth since the Three Mile Island (TMI) incident in 1979. After more than 30 years, the nuclear community is at a stage where the need for more advanced and modern reactors is apparent. This imminent nuclear "renaissance" is motivated by the need for increased work efficiency, component obsolescence, international competition and increasing energy demand. As a result, the nuclear industry in the United States, and specifically nuclear power plant (NPP) control rooms, are undergoing extensive modernization. In addition, recent initiatives promise the construction of new and advanced plants to be built over the next few years (Schmidt, 2010). The new reactors will have advanced and computerized control rooms. The next-generation control rooms will have different tools with different functionality, more automation and more dynamic information to display. The type of information presentation has also changed from mechanical gauges and analog panels to large screen and touch-screen digital displays (Figure 1).

Although advanced technologies may enable a more efficient working environment and provide more functionality, they may introduce additional complexity to the NPP operations in general. Although complexity has turned out to be a very difficult and abstract construct to define, a general understanding of system complexity has something to do with interconnections between parts. In addition, size and variety of system elements has an effect on human information processing and hence could affect a control room being perceived as complex or not (see Chapter 2 for a discussion of complexity definitions).

Investigating the effects of control room modernization is important since personnel in such environments must deal with increasing amounts of advanced technologies, such as large screen and multiple displays. Unfortunately, the literature in the fields of Human-Computer Interaction (HCI) and Human Factors (HF) lacks a clear description of sources that could contribute to perceived complexity of the operators. Modern and computerized control rooms of the future may challenge human operators' cognitive abilities by presenting information in complex ways. It is critical that new reactor control rooms are designed and built with the cognitive needs of operators at the forefront. Without proper understanding and management of the sources that contribute to the complexity of control room environments, these sources may degrade human performance. It is vital to understand the negative effects of complexity on human performance, as human errors are not affordable in the NPP operations due to the safety-critical nature of such operations.

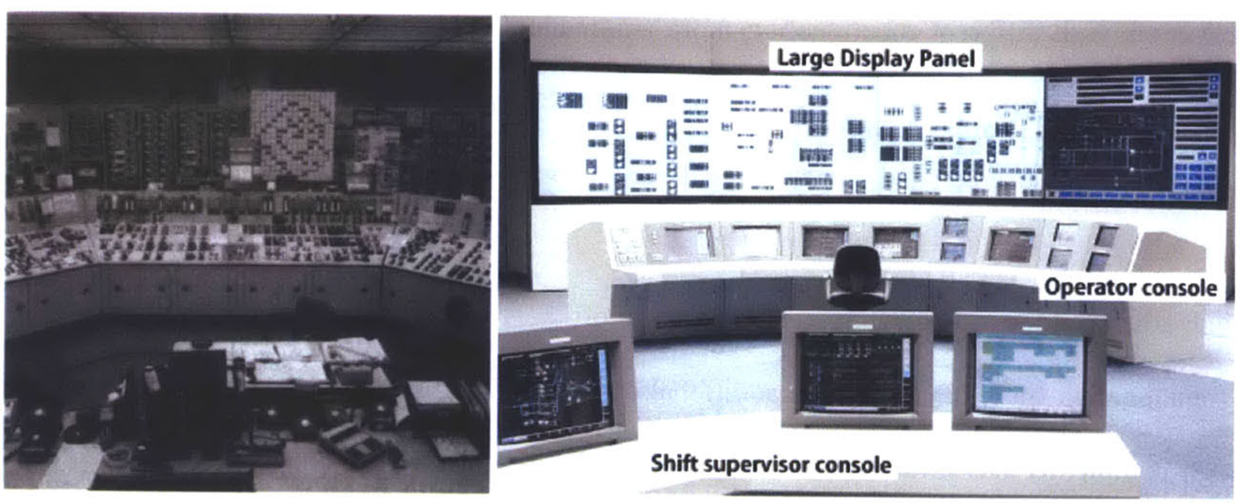


Figure 1. A traditional control room (left)[1] vs. an advanced control room (right)[2]

[1] Source: http://theragblog.blogspot.com
[2] Source: http://www.mhi.co.jp/atom/hq/atome_e/apwr/04.html

Currently, the Nuclear Regulatory Commission (NRC) is responsible for the approval of new control room designs. As a result, it is vital to provide the NRC staff with a technical basis to understand the human performance effects of modernization changes and enable them to assess the acceptability of new designs in terms of safety. One of the most important research topics identified both by previous NRC research (O'Hara, 2009) and the Organization for Economic Cooperation and Development Work Group of Human and Organizational Factors (NEA/CSNI, 2007), is "Human-System-Interface (HSI) complexity and opacity". These efforts identified the need for further investigation of the limitations of human cognitive abilities and the effects of information overload. Of particular interest in this domain is to understand that the sources of complexity are essential factors in predicting human reliability in HSIs of NPP control rooms. Although research in other similar domains such as aviation (e.g. Xing, 2004; Cummings & Tsonis, 2006) shed some light on possible sources of display complexity, the exact nature of these sources in the NPP domain needs further investigation.

1.2 Research Goals

The main objective of this research is to identify factors that contribute to complexity in existing and advanced nuclear power plant systems and Human-System Interfaces. The addition of new computerized systems to the NPP operations environment may have negative effects on human performance due to added complexity. This research provides the building blocks for understanding the sources that contribute to increased complexity and a major move towards developing taxonomy of such sources. Regulatory agents such as the NRC's human factors engineering reviewers could benefit from such taxonomy in their safety and licensing activities for new and advanced control rooms.

1.3 Thesis Overview

This thesis is organized into the following chapters:

- Chapter 1, *Introduction*: Motivates the importance of understanding and investigating sources that contribute to operators' perceived complexity in human supervisory control domains. In particular, the introduction of next generation nuclear power plant control rooms is discussed as a potential problem with regards to unknown nature of complexity that the new technology provides.
- Chapter 2, *Background*: Reviews several definitions of complexity in the literature and discusses the common features in these definitions. Two broad views on complexity are discussed, objective and subjective complexity.
- Chapter 3, *Complexity Investigation Model*: Introduces a model to investigate complexity both subjectively and objectively while looking at the difference between the two. The Complexity Investigation Model also considers the difference between the complexity views of the three groups of stakeholders: Operators, Designers and NRC Reviewers.
- Chapter 4, *Methodology*: Describes a 5-step iterative methodology to identify and evaluate sources of complexity and potential interactions between them. The following steps are discussed in detail: *Step 1*: identifying the complexity sources using a combination of methods, *Step 2*: collecting objective evidence for the sources by conducting a content analysis of 22 previous nuclear incidents, *Step 3*: representing the potential interactions between the sources via a network representation, *Step 4*: collecting subjective views of different stakeholder groups using a survey-interview method, and *Step 5*: identifying variations between the objective complexity evidence and subjective

stakeholders views on complexity as well as differences between the complexity views of different stakeholder groups.

- Chapter 5, *Results*: Discusses the analysis of variations between the objective evidence and subjective complexity views of the stakeholder groups. In addition, a qualitative analysis of the difference between the stakeholder views on several important sources of perceived complexity is discussed. Finally, a qualitative analysis of interview-survey data is discussed.
- Chapter 6, *Discussion and Future Work*: Describes the overall findings of this research and proposes potential areas of research to complement and extend the work done in this thesis.

2. BACKGROUND

In order to provide a foundation to understand complexity in the context of NPP control rooms, an extensive literature review of different disciplines was conducted. This chapter summarizes the related literature, introduces several important complexity definitions and their common features, and discusses several important research gaps.

2.1 Complexity Definitions

The term "complexity" comes from the Latin word "Complexus", which means, "to twine" as defined in the *Merriam-Webster* dictionary (http://www.merriam-webster.com). Complexity is defined in various ways across diverse disciplines and in relation to various systems. Although several rich interpretations of complexity in different disciplines have been offered (Table 1), it is still unclear what exactly makes a system "complex" and how this complexity and its effects on human performance can be measured. This research gap is, in part, due to oversimplification of scientific or philosophical explanations of real world phenomena or the so called "complexity science" (Dent, 1999). Some of the most-used definitions of complexity are often tied to a collection of inter-connected parts, or so called "systems". Some give emphasis to the complexity of a system's behavior, while others focus on the internal structure of the system.

Table 1. Different definitions of complexity (modified from Xing & Manning, 2005)

SOURCE	DEFINITION
General understanding (Xing & Manning, 2005)	Size (of parts), variety (of parts) and rules/interconnections (between the parts)
Algorithmic Complexity by Rouse and Rouse (1979)	Computational complexity of the algorithm used to solve the problem
Complexity by Drozdz (2002)	A trinity of comprising coherence, chaos and a gap between them
Complexity by Johnson (2007)	Number and type of Parts and their interconnections, System's memory and feedback, The relationship between the system and environment is non-linear, the system can adapt itself according to its history
Kolmogorov complexity (Casti 1979)	Minimum description size
Weaver complexity (1948)	The difficulty of predicting the properties of the system, given the properties of the parts
Effective Measure Complexity (Grassberger 1986)	The amount of information that must be stored in order to make an optimal prediction about the next symbol to the level of granularity
Topological complexity Crutchfield and Young (1989)	The minimal size of the automaton that can statistically reproduce the observed data within a specified tolerance
Simon's complexity (1962)	Near-decomposable hierarchic structure
Complexity by Langton (1991)	Level of mutual information, which measures the correlation between information at sites separated by time and space
Bennett logical depth (Bennett 1990)	Computational cost (time and memory) taken to calculate the shortest process that can reproduce a given object
Hieratical complexity (Bates and Shepard 1993)	Number of local states, dimensionality and rule-range
Cyclomatic complexity (McCabe 1976)	Difference of the total number of transitions and the total number of states
Edmonds's complexity (Edmonds 1999)	The difficulty to formulate an overall behavior with given atomic components and their inter-relations
Cognitive complexity (Crokett 1965)	The entities of differentiation, articulation and hierarchic integration
Bieri's index of cognitive complexity (Bieri 1955)	Number of constructs and matches between the constructs
Relational complexity (Halford et al. 1998)	The number of interacting variables that must be presented in parallel to perform a process entailed in a task
Kauffman complexity (Kauffman 1993)	Number of conflicting constraints

In many of these definitions, however, complexity in the context of HSI contains several common components. In particular, complexity has been defined in terms of three separate dimensions within a particular system: quantity, variety, and interconnections (Xing and Manning, 2005; Xing, 2007). Quantity refers to the number of items in a certain part of the system. This quantity could be, in the context of HSI in NPP control rooms, the number of displays in the control room, the number of buttons on a control panel, number of icons on a particular display, or the number of sub-systems within an overall system. Variety is the number of different components in the system. Variety could refer to the number of different kinds of buttons on an NPP control panel, the number of different colors in a particular display, the number of different size displays, or the number of different types of pumps in a system.

Interconnections describe the links between components of a system. Although size and variety (of elements) are measurable in a given system, interconnections can be difficult to quantify in the system, unless all system states are known. For instance, increasing the temperature of water in a holding tank could cause an automatic increase in the flow rate from the tank to a heat exchanger. This "cause and effect" type of interconnection is just one example of the various couplings and links that can occur in a given system, and thus they are inherent to the notion of complexity. Perrow (1999) explains complexity in terms of interactions among subsystems (from linear to complex) and coupling of parts (from loose to tight). Perrow argues that our systems have become so complex and tightly coupled that accidents are inevitable and are considered "normal". He defines linear systems as systems in which interaction between the parts are expected in a sequence. This is in contrast with complex systems in which the interactions between the parts are unexpected.

This generic description of complexity is useful to understand the basis of the variety of complexities that have been identified in the literature. As shown in Table 1, nearly all the complexities in the literature are defined in terms of quantity, variety, and interconnections, though the measurement of these components is highly dependent on the domain. For the purposes of this research, I shall define complexity of a system simply as *the number and variety of system elements, and the number of interconnections between them.*

2.2 Objective Complexity

Broadly stated, complexity in NPP control rooms could be explained both objectively and subjectively. "Objective complexity", also known as "descriptive complexity" (Schlindwein and Ison, 2004), has been defined as an inherent property of a system or the environment surrounding a system. This objectivist view of complexity is dominant among scientific communities, and is responsible for most of the quantitative attempts to measure complexity. Proponents of this ideology argue that the characteristics of complex systems are not merely what humans perceive; there exists an objective reality for each system independent of the observer (e.g., Cilliers, 1998; Rescher, 1998).

Although a vast amount of objective data are potentially available from NPP control rooms, derivation of a meaningful and reliable list of factors that may contribute to the complexity of such systems is missing from the existing research. One approach to investigate the objective sources of complexity in the NPP control room environments is to study and analyze real world incidents. The Nuclear Regulatory Commission (NRC) maintains several incident report databases that could be used as plausible resources to discover the systematic factors or sources of complexity, including human error, which led to previous accidents. This concept is further explored in Chapter 4. One of the limitations of this approach is the influence of the subjective views of the humans involved in preparation of such incident reports. This makes the data from incident reports quasi-objective. Earl Babbie (2010) posits: "Objectivity is a conceptual attempt to get beyond our individual views. It is ultimately a matter of communication, as you and I attempt to find a common ground in our subjective experiences." (p. 42). Although there is some subjectivity involved in how these reports are created, the data from incident report databases are arguably a plausible resource to reflect objective reality, or what Babbie calls the "Agreement Reality", since such reports are subject to significant review and regulatory agency endorsement.

2.3 Subjective Complexity

Alternatively, "subjective complexity" describes complexity as the unique understanding of a phenomenon by a human observer. In other words, complexity is dependent on human perception; thus, each person in the nuclear power industry has a different interpretation of complexity based on his or her mental model. This epistemological view of complexity is also known as "perceived complexity." For proponents of this view (e.g., Le Moigne, 1990; Casti, 1995; Martinez, 2001), complexity is an inherently subjective concept. Intuitively, perceived complexity of a complex environment, such as a NPP control room, could be correlated with the operator's performance. Previous research shows that increased perceived complexity of the system in supervisory control environments, such as air traffic control, can reduce operator performance (Xing, 2004; Cummings et al., 2008).

For the purposes of subjective complexity data gathering in this research, three broad categories of NPP stakeholders were identified based on the assumption that each group represents a homogenous view of complexity (this assumption is discussed in Chapter 6). The stakeholder groups identified were: 1) Control room operators or the end users, 2) Original Equipment Manufacturers (OEMs), or the designers, and 3) NRC design reviewers that represent the regulatory body. These key stakeholders are mostly responsible for the design, acquisition and operation of NPP control rooms, and therefore, play an important role in complexity of the control rooms. Therefore, it is important to ensure that their views on the effect of complexity on human performance matches the objective reality reflected by previous NPP accidents and incidents.

2.4 Objective vs. Subjective Complexity

An historical analysis of complexity literature shows that strategies for studying complexity are not comprehensive enough and complexity distinctions are, in some sense, biased through either the objective or subjective outlook particular researchers adopt regarding complexity (Schlindwein and Ison, 2004). A more systematic approach, which takes into account the interconnections between the observer and the observed, is missing from existing approaches. A complete separation of object and subject will result in an inconclusive complexity knowledge base (Ciurana, 2004). Understanding complexity should involve a trans-disciplinary investigation of both system properties as well as the stakeholders' views of complexity.

In conclusion, the review of the complexity literature presented in this chapter showed the connection of three important concepts to system complexity: size or number of parts, variety of parts, and interactions between them. This chapter also discussed the two dominant views on complexity: objective complexity and subjective complexity, and motivated the importance of considering both in understanding and investigating complexity. The next chapter introduces a holistic model to guide the investigation of complexity in human-supervisory control systems, which considers both the objective evidence from the past incidents and the subjective views of several stakeholder groups as well as the difference between the two. Using the model, several fundamental research questions are raised.

3. COMPLEXITY INVESTIGATION MODEL

Understanding and measuring sources of complexity both subjectively and objectively is an essential step in systematic conceptualization and operationalization of complexity as an abstract construct. We hypothesize that stakeholder groups may have constructed an unrealistic or an incomplete mental model of the factors that make a control room complex. This misunderstanding might affect their behaviors and eventually the technologies they design, approve or manipulate. As a result, a mismatch between the perceptions of operators, control room designers and NRC reviewers regarding the effects of complexity and the actual objective data about the effects of complexity of control rooms (shown as "Δ" in Figure 2) could be problematic. A differential in complexity mental models introduces additional uncertainty to the system, which could result in increased operator errors, ineffective designs and risky acquisition decisions. Understanding these potential discrepancies is essential for designers and evaluators, as synchronizing the perceived complexity of different stakeholders and the actual complexity in the contextual domain in a reductionist manner may lead to designs that could be less prone to risk.

As shown in Figure 2, incident report databases such as Human Event Repository and Analysis (HERA), Licensee Event Report (LER) and Human System Information System (HSIS), could be used as plausible resources to gather objective evidence for the sources that contributed negatively to the perceived complexity of the operators in previous incidents. Such objective evidence then could be compared to the subjective views of the stakeholders to identify potential disparities.

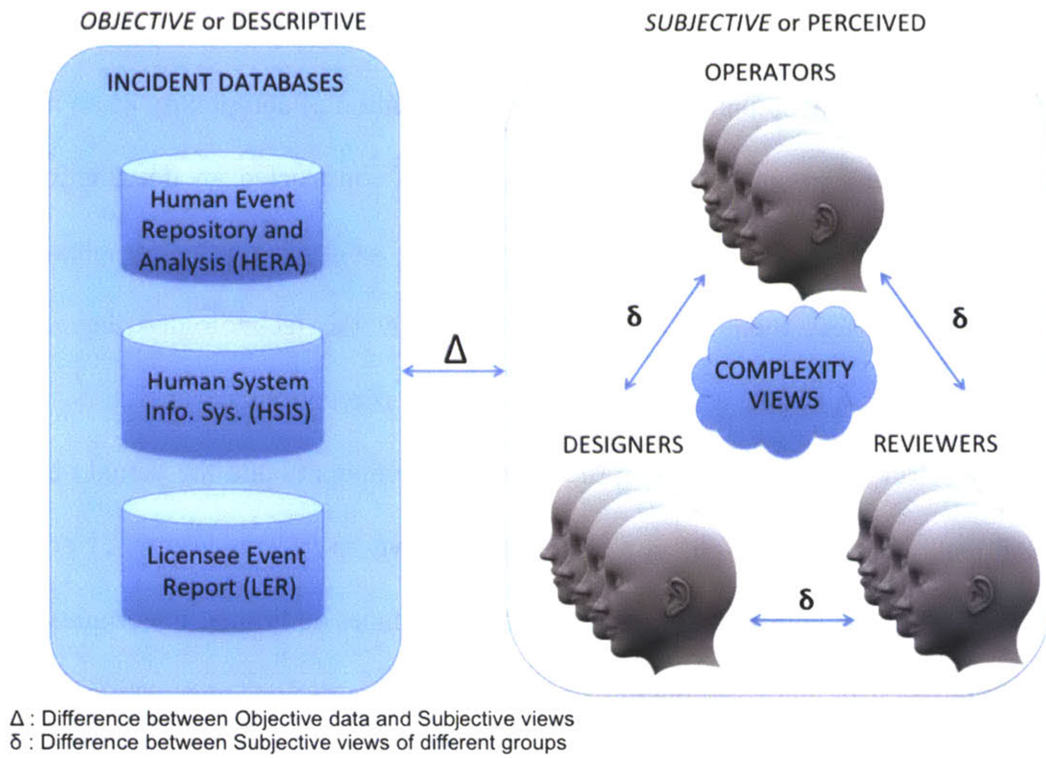


Figure 2. Complexity investigation model. The differences between subjective complexity and objective complexity ("Δ"). Differences between complexity views of the control room design stakeholders ("δ")

3.1 Conflicts in Stakeholder Complexity Views

As discussed in the previous section, three broad groups of stakeholders were identified based on the important role they play with regards to complexity of the system: Operators, control room Designers and NRC Reviewers. Operators are highly trained controllers in charge of monitoring the health and status of the reactors. Operators are considered the end-user of the control room system. Mitigating the negative effects of the perceived complexity of the control rooms on their performance is the ultimate goal of this research. Designers are in charge of the design and architecture of NPP control rooms. Designers are considered key stakeholders since their design decisions will directly affect the structural and functional complexity of the control rooms. NRC reviewers are safety experts who review reactor designs in order to identify major safety and technical issues. Reviewers play an important role as an interface between the operators and designers by evaluating the aspects of the design that might hinder operator performance.

One of the hypotheses of this research is that the NPP stakeholder groups could have different mental models of NPP control rooms and, hence, their perceived complexity of such complex systems differs. Without understanding such intra-organizational imbalances in complexity views, it is questionable whether safety measures will guarantee system safety. To date, no guidelines or methodologies have been developed to systematically investigate these complexity differences. This research proposes a novel method to 1) help understand the aspects of a control room that make it complex, 2) to investigate imbalances between objective and subjective complexities in relation to human performance, and 3) to examine three different intra-organizational comparisons between different stakeholders, namely operators-designers, designers-reviewers and reviewers-operators (shown as "δ" in Figure 2). These pairwise comparisons are explained below:

Operator-Designer: Previous research implicates human error as the main causal factor for almost 70% of accidents in safety-critical systems (Stanton et al., 2010). Although extensive programs are in place to review the safety of new control rooms, it is still not clear which aspects of a control room contribute to increasing perceived complexity and how this complexity affects an operator's performance. On the other hand, control room designers are responsible for identifying the error potentials in the design process and are required to conform to the NRC's design and human factors standards (O'Hara et al., 2004). Therefore, designers should adopt strategies to identify complexity-induced human error potentials within the system and mitigate sources that exacerbate perceived complexity. Large discrepancies in complexity views of control room designers and operators is a serious issue, which would demonstrate that users' perceived complexity is not properly understood. Hence, some of the potential sources for human error may not be considered in the design. In other words, without understanding the sources that contribute to operators perceiving the control room as complex, designers are merely designing control rooms based on their own mental models of complexity. The effects of such disparity is apparent in the Three Mile Island incident in which ambiguous control room instruments and indicators resulted in the failure of plant operators to recognize the problematic situation (i.e., operators were not aware of a stuck-open pilot-operated relief valve (PORV) that caused a large amount of coolant to escape). The propagation of effects was compounded by large amount of irrelevant, misleading or incorrect information presented to the operators (Kemeny, 1979).

Designer-Reviewer: The NRC's responsibility is not only to protect the health and safety of the public and environment by ensuring that adequate training is provided to operation staff, but also to regulate the design of the new power plants. Designs of new control rooms undergo an extensive Human Factors Engineering (HFE) review in which the applicant's HFE program would be verified against accepted HFE practices and guidelines. In order to support the review and licensing of advanced reactor designs, the NRC has adopted an anticipatory design research approach to understand safety issues that might evolve in future designs. In this approach, the

NRC uses so called "Surrogates" which are similar advanced control rooms from different domains (e.g. process control) to build technical guidelines that facilitate the design review process for future designs. Differences in complexity views between designers and reviewers is problematic because, without knowing how control room designers think about complexity, the NRC's regulatory decision-making efforts are less informed and may result in risky acquisitions. In addition, a mutual understanding of the control room features that affect complexity bolster collaboration between OEMs and the NRC, making the mutual expectations more transparent.

Reviewer-Operator: As part of human factors Verification and Validation (V&V), NRC reviewers evaluate the design of the control rooms to verify that the design accommodates human abilities and limitations using the guidelines documented in NRC's Human-System Interface Design Review Guideline or NUREG-0700 (O'Hara et al., 2002). However, NUREG-0700 doesn't provide any guidelines with regards to perceived human complexity. Understanding the differences between complexity views of the NPP operation staff and NRC reviewers is essential in developing comprehensive HFE review guidelines in which the effects of complexity on human performance are incorporated.

Such pairwise comparisons shed some light on intra-organizational conflicts in complexity views. This information is vital in developing design standards and guidelines that consider human cognitive limitations with regards to perceived complexity. In addition, potential disparities in complexity views of stakeholders show the need for developing a standard framework for thinking about such an important issue and potential policies to align such views.

3.2 Research Questions

As discussed in the previous sections, understanding the sources of complexity in the context of the nuclear power plant control rooms is critical given the modernization of current plants and the addition of new plants. In addition, the disparities between different stakeholder complexity views (i.e., subjective complexity), and the actual world complexity (i.e., objective complexity) as well between-group differences in complexity views needs to be investigated further. This leads to three fundamental research questions (also see Figure 3):

1. What factors contribute to the complexity of an NPP control room and more generally, in Human Supervisory Control (HSC) systems?
2. Are there large variations between objective complexity data and subjective complexity views, and what are the implications?
3. Are there large variations between the operators, designers and regulators views on complexity, and what are the implications?

In order to address the above-mentioned research questions, next chapter introduces a novel methodology to identify potential sources of perceived complexity, collect objective evidence for the identified sources, collect subjective complexity views from the stakeholders, and to identify variations between the objective evidence and the subjective stakeholder views. The method also considers the intra-organizational differences between the stakeholder groups' complexity views.

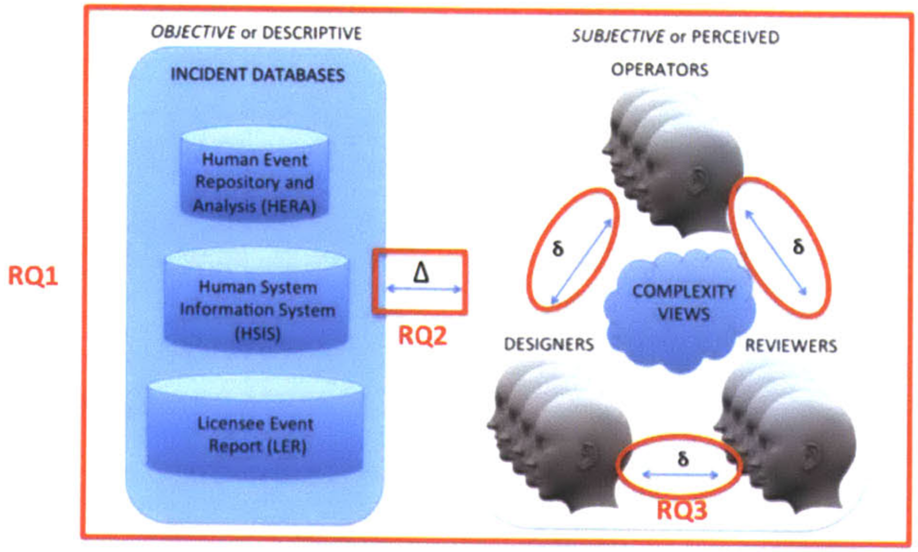


Figure 3. Research questions (RQ1: research question 1, etc.) embedded in the complexity investigation model

4. METHODOLOGY

In order to address the abovementioned questions, this research introduces a 5-step iterative methodology (Figure 4) to investigate important sources of complexity in the NPP control environment that have an impact on human performance both objectively and subjectively, while examining the difference between the two. Interconnections between sources are reviewed to further understand the overall complexity of NPP systems. In addition, different categorizations of complexity are introduced to better organize various aspects of complexity. Each of the steps in the methodology will be reviewed in detail in the following sections.

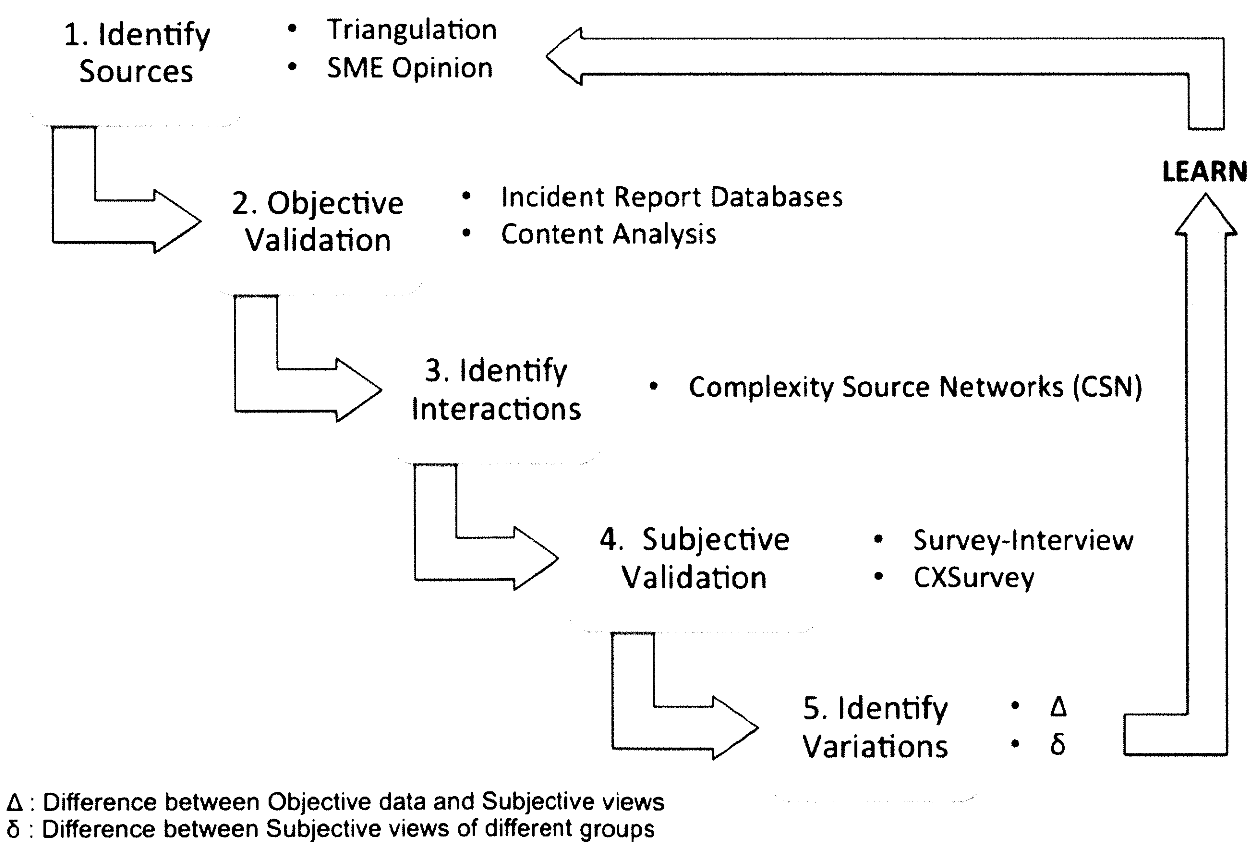


Figure 4. Complexity investigation methodology

4.1 Step 1: Identification of Complexity Sources

One of the most important goals of this research is to identify the factors that contribute to complexity in NPP control rooms (research question 1). In order to identify potential sources of complexity in NPP control rooms in the United States, a triangulation method was used which incorporated multiple methods. First, literature was reviewed for empirical evidence for the existence of such sources in similar domains. In particular, previous research in the field of aviation provided insight on potential sources of perceived complexity in air traffic control (ATC) control rooms (e.g. Xing & Manning, 2005; Cummings & Tsonis, 2006; Xing, 2007). Next, a field study at the Massachusetts Institute of Technology (MIT) nuclear reactor was conducted, including extensive interviews with reactor personnel. Next, plant operations at several different facilities were observed, including the Pilgrim Nuclear Power Station, the NRC Technical Training Center (TTC) simulator and the New York Independent Systems Operator (NYISO) electricity distribution control room. In addition, an online questionnaire was designed to obtain data from operators in terms of what they perceived as contributors to their job complexity (Cummings et al., 2010, Appendix A). Finally, several subject matter experts (SMEs) experienced in nuclear operations were identified and interviewed to offer their opinion on sources of complexity. The qualitative analysis of gathered data led to the generation of an initial list of complexity sources in NPP control rooms (see Appendix B.1). The next step in the methodology is to collect objective evidence for the identified sources, which is discussed in the next section.

4.2 Step 2: Objective Validation

In order to gather objective evidence for the identified sources and their effects on human performance (research question 2), several NRC-maintained incident databases, including Licensee Event Reports (LER), Human Factors Information System (HFIS), and in particular, Human Event Repository and Analysis (HERA) were parsed for complexity-related operator mistakes and errors.

4.2.1 Content analysis of HERA

HERA is an incident report database designed to make available empirical human performance as well as system fault data from 22 commercial nuclear plant incidents. The HERA database was originally designed by NRC researchers to support their Human Reliability Analysis (HRA) research. Therefore, the incidents in HERA were chosen based on the availability and the quality of information as potential HRA data sources. In particular, the initial extraction of data into HERA has focused on four groups of incidents: Events involving emergency diesel generators, events involving initiating events, events involving common-cause failures, and events with significant risk of conditional core damage probability (CCDP) (see NUREG/CR-6903 for a discussion of selection criteria). Each incident in HERA is broken down into hundreds of sub-events that provide the chronological sequence of human, equipment and off-plant sub-events. HERA uses sub-event codes to categorize the negative or positive effects of the sub-events (see Table 2).

Table 2. The HERA Sub-event Codes (Hallbert et al., 2006)

	Negative Outcome	Positive Outcome	Contextual Info
Human	XHE	HS	CI
Plant	XEQ	EQA	PS
External	EE	EE	EE

Where,

- ***XHE***—represents a human error (HE) that potentially contributes to the fault (X). An XHE is a human action or inaction that:
    - Occurs within the boundary of the nuclear steam supply system (NSSS) and balance of plant (BOP) systems; *AND*
    - Is unsafe; *OR*
    - Potentially negatively affects plant, system, equipment availability, operability, and consequences; *OR*
    - Represents circumvention with negative impact.

- ***HS***—represents a successful human action or inaction that potentially has a positive effect on the event outcome. HS is a human action or inaction that:
    - Occurs within the boundary of the NSSS and BOP systems; *AND*
    - Potentially positively affects plant, system, equipment availability, operability, and consequences; *AND*
    - Represents activities that are not purely routine and that go beyond normal job expectations; *OR*
    - Represents a recovery action; *OR*
    - Represents circumvention with positive impact.

- ***CI***—represents contextual information about the human action or inaction. It is any human action or inaction that isn't classified as an XHE or HS. Specifically, CI is a human action or inaction that:
    - Is associated with design errors or improper guidance; OR
    - Takes place outside the NSSS and BOP systems; OR
    - Is an engineering function including onsite engineering; OR
    - Represents expected human actions in response to the situation; OR
    - Encompasses conversations and notifications.

- ***XEQ***—represents an equipment failure (EQ) that potentially contributes to the fault (X).

- ***EQA***—represents successful equipment actuation that potentially has a positive effect on the event outcome.

- ***PS***—represents information about the plant state that helps to explain the equipment failure, actuation, or other noteworthy factors pertaining to plant health or transients.

- ***EE***—represents events external to the plant such as extreme weather, external fires, seismic events, or transmission system events.

An enormous amount of detailed information regarding each sub-event, including the event summary, key human performance insights provided by HERA coders and accident investigators, as well as a timeline of events, makes possible a systematic analysis to identify a chronological progression of human actions, inactions and interactions within the plants. Such strong deconstructionism (i.e., in terms of creating the chain of events) and dualism (i.e., looking at both human and system faults) (Dekker, 2005) qualities make HERA a valuable resource for gathering objective complexity data for control rooms, specifically in reference to human performance.

Three evaluators (two undergraduate, and one graduate student at MIT) parsed HERA for the existence of evidence to support the identified sources of complexity as well as to identify new sources based on the incident reports data. The 22 incidents in the HERA database include two types of events: *near misses* (narrowly avoided catastrophic situations) or *minor events*, such as a small atmospheric release of radioactive effluents. Each event was carefully examined and parsed, resulting in a large collection of individual actions taken before, during, and after the event. Each particular action was coded according to conventional probabilistic risk assessment (PRA) methods (Halbert et al., 2006). Each of the 22 events in the HERA database was examined for the performance-shaping factor (PSF) class of complexity. Each of the PSFs that were coded as a human error (XHE) or human success (HS) due to complexity were examined and recorded (Appendix C). Two particular factors occurred quite frequently: "Simultaneous tasks with high attention demands" and "Problems in differentiating important from less important information". These factors translated to sources of complexity concerning parallel tasks and procedures and can also be related to several sources within the interface complexity category.

An inter-coder reliability assessment was performed to ensure consistency between the three evaluators (Lombard et al., 2002). The result of the inter-coder reliability assessment showed 85% agreement in the identified source evidences and the inconsistent source evidence instances were removed from the evidence database. Although content analysis is very useful for analyzing historical data and is promising to collect plausibly objective evidence for complexity sources, it suffers from several limitations. Firstly, the analysis is limited by the availability of material. The HERA database is by no means a collectively exhaustive set of nuclear incidents in the United States. Secondly, although the analysis is geared toward producing objective evidence for the complexity sources, the data included in the HERA database are exposed to the subjectivity of the HERA coders. In particular, the inferential procedures followed by the initial HERA coders are not well documented.

The qualitative content analysis of the incident report databases, and in particular the 22 incidents in HERA, resulted in an evidence database that holds a collection of sub-event codes for different incidents that support the existence of particular complexity sources. As shown in Figure 5, the first column in the database lists the sources of complexity identified using the methods previously discussed. The remaining columns represent data from a specific incident in HERA. Each cell contains sub-event codes (Table 2) that support the existence of a complexity source. The terminology HERA uses is commonly used in the HRA and probabilistic risk analysis (PRA) communities and was generated by NRC research staff (Hallbert et al., 2006). As previously discussed, each incident in HERA is subdivided into hundreds of sub-events that provide the timeline of events. As shown in Table 2, each sub-event was coded based on the type of information it contains and is sequentially numbered (e.g., XHE 1, XHE 2, etc.). For example, as shown in Figure 5, four types of sub-events were used to support "available time" in the "Browns Ferry 1" incident: 12 successful human actions (HS) sub-events, 2 contextual information (CI) sub-events, 12 human error or fault (XHE) sub-events, and 2 plant state (PS) sub-events.

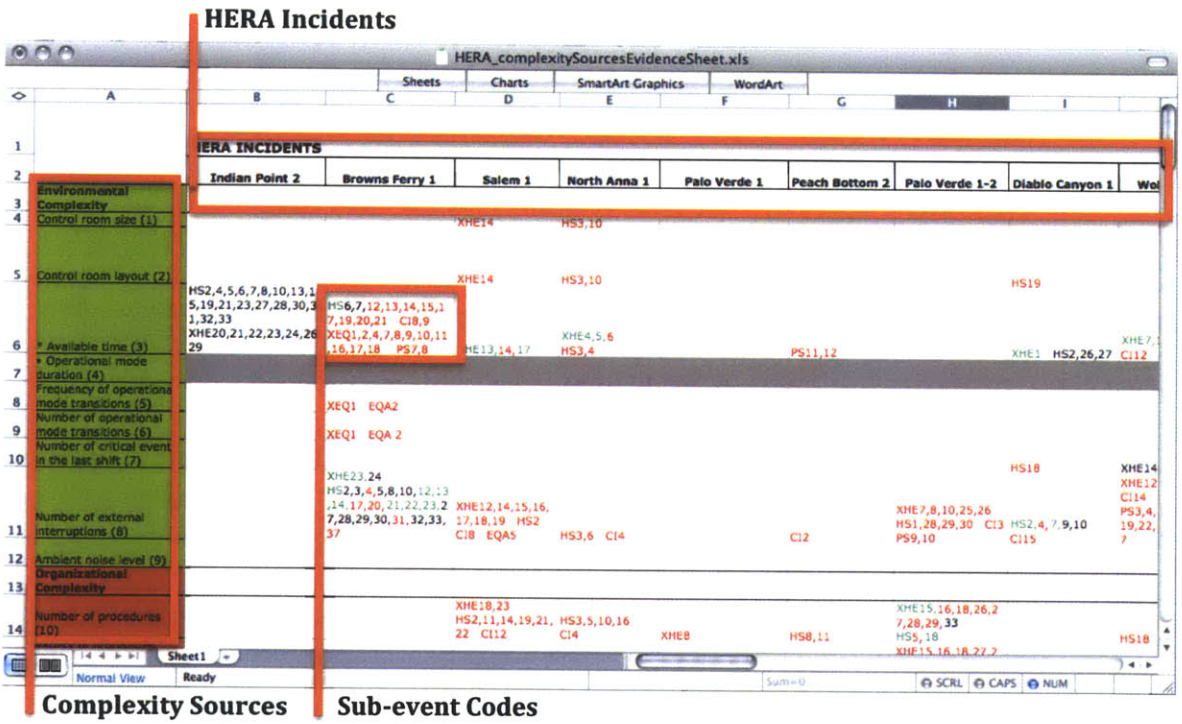


Figure 5. Complexity source evidence database

Although HERA provides a vast amount of information for each incident, a systematic investigation of these incidents that considers the interactions between the system components is missing in HERA. In order to address this issue, a Systems-Theoretic Accident Modeling and Processes (STAMP) analysis can be conducted on the incidents in HERA. STAMP is a causality model based on systems theory (Leveson, 1995; 2009). STAMP analysis goes beyond identifying direct system failures or human error and looks at identifying the main stakeholders within the hierarchical control structure and how the interaction between the actions or inactions of these stakeholders contributes to the incidents under investigation. Due to time and resource limitations only one STAMP analysis was conducted on the Salem Unit 1 incident, which has the largest number of interconnections (Appendix D). The STAMP analysis resulted in identification of some of systematic factors that contributed to the incident under investigation and revealed several additional sources of complexity (Appendix B.2).

In summary, an evidence-based approach was used to provide evidence for and to validate the identified sources of complexity objectively using a systematic analysis of previous incidents. This resulted in an evidence database that could be used for objective validation of sources. As discussed in Chapter 2, identifying interactions between the subparts or events in complex systems is overly challenging. The next section describes a method to identify some of the potential interactions between the sources of complexity in nuclear incidents.

4.3 Step 3: Identification of Interactions

4.3.1 Network Models

NPPs are complex socio-technical systems with many discrete parts, which are not uniformly connected. The existence of human operators as part of the system creates additional interrelations between the sub-parts of the system and humans, and introduces more uncertainty. For such complex systems, understanding the building blocks is not enough to understand the overall system. For that reason many classical models fail to accurately represent such systems. Network theory is an established field of research and is considered one of the forerunners of the complex systems research (Wasserman, 1994; Newman, 2010). Using this theory, graphs are used to represent real world phenomenon and more specifically, to represent the asymmetric relationship between the parts of a system.

A popular theory among complexity scientists is that the number of individual components and their connections has been described as a direct measure of complexity (Edmonds, 1995), which makes network theory an excellent candidate to represent and analyze complex systems. Network theory provides tools to deal with many nodes and their structural and statistical properties. When a system is represented as a network, network theory provides insight on the shape of the networks (e.g., the form of overall interaction), their growth (e.g., how did the interactions between the sources emerge over time), connectivity (e.g., how easily the negative effects propagates through the network), and robustness (e.g., identifying the critical nodes/links without which the network loses its connectivity significantly).

Overall, the concept of complexity versus simplicity can be understood in the context of networks. Usually complexity of the network is attributed to the number of nodes and interconnections between them. For example, a fully connected network (a network in which all the nodes are connected to each other) with 200 nodes is considered more complex than a network with 100 nodes that are not all connected with links. By presenting complex systems as networks, the problem of reducing (or increasing) complexity becomes more straightforward (e.g. reducing/increasing the number of nodes/links). Network theory also provides answers to some important questions with regards to complexity such as what makes some nodes more connected than the others. What are the areas of high cohesive connectivity (these are groups of nodes that are highly connected)? How can we reduce/increase the overall connectivity of the network? How do networks emerge over time or during different phases of operation? The next section introduces a network to represent sources of complexity and their interconnections

4.3.2 Complexity Source Networks

The identification of interactions between the sources of complexity is important in order to understand the overall complexity of the NPP control room environment. Due to the richness of incident information included in the HERA database, the interconnections between NPP sources of complexity can be represented and explored via a network representation. A Complexity Source Network (CSN) was used to represent the identified sources of complexity and their interrelations for each incident (Figure 6). In a CSN, nodes represent sources of complexity and links between two nodes represent the interactions between the sources. These interactions are captured as the co-occurrence of those sources within a single sub-event in a particular incident. For example, as shown in Figure 7, since the complexity sources "Number of external interruptions" and "Number of parallel procedures" were identified as the contributors to the sub-event "XHE12" (i.e., the twelfth human fault-related sub-event) in the Salem 1 incident, the two nodes are connected with a link (see Appendix E for complete set of CSNs for 22 incidents included in HERA).

As discussed in section 4.2, when a source is identified to be a contributor to a sub-event in an incident in HERA, that sub-event code (e.g., XHE12, HS1, etc.) is used as the evidence for the existence of that source and is collected in an evidence database (Figure 5). The weight for a node in a CSN corresponds to the total number of evidences (i.e., sub-event codes) collected in a particular cell in the evidence database that corresponds to that source (i.e., node) for the incident under investigation. For example, since 10 sub-event codes were collected to support the source "Number of external interruptions" for the Salem 1 incident, the weight 10 was assigned to its corresponding node. On the other hand, the weight for a link between two nodes in a CSN corresponds to the number of common sub-event codes between those two nodes. For example, since there are 7 common sub-events to support both "Number of external interruptions" and "Number of parallel procedures" (i.e., XHE 12, 15, 16, 17, 18, 19 and HS2), the weight 7 was assigned to the link connecting the two (Figure 7). As shown in Figure 6 and 7, the nodes were color coded to show four different levels of complexity: environmental complexity (green), organizational complexity (red), interface complexity (blue), and cognitive complexity (black). These categories are part of a so-called Human-Supervisory Control (HSC) complexity chain, which is discussed in the next section.

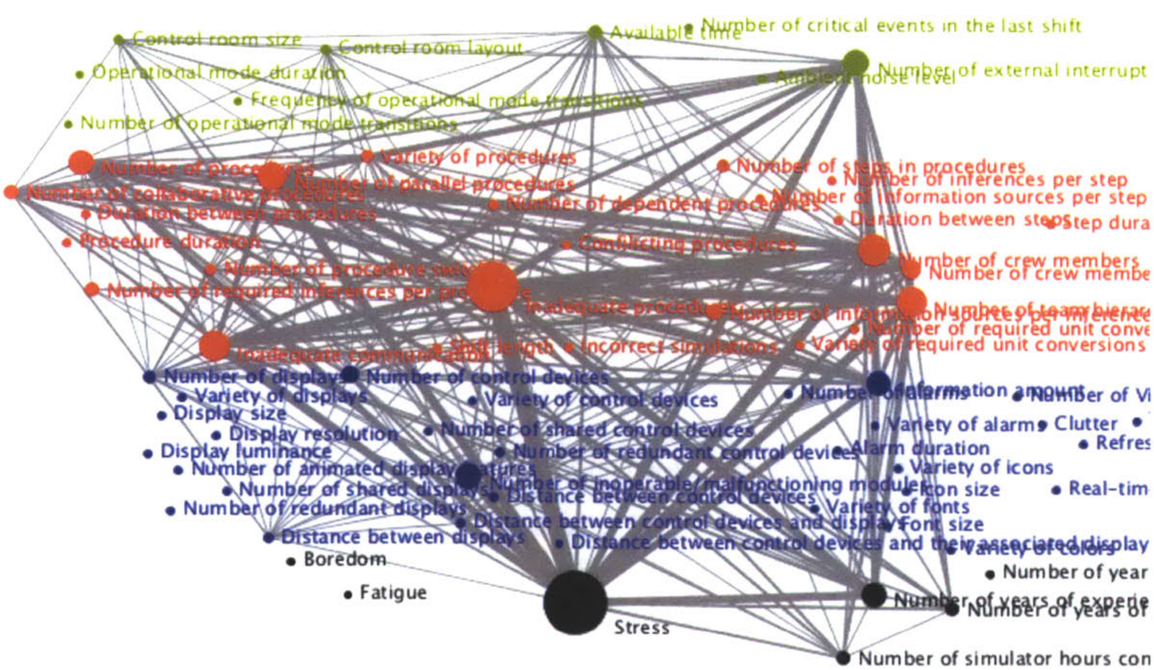


Figure 6. Complexity Source Network (CSN) for the Salem unit 1 incident

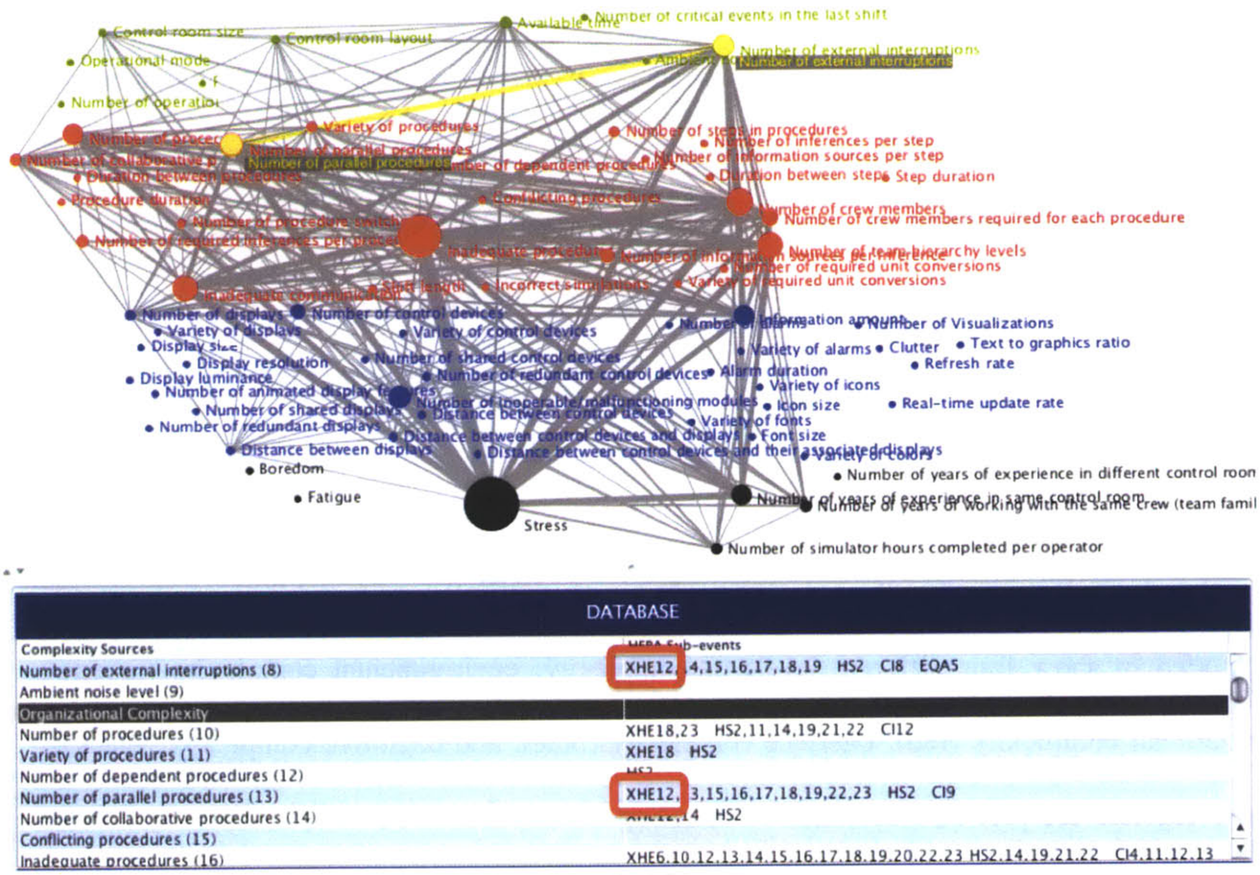


Figure 7. Interaction between the two sources of complexity "Number of external interruptions" and "Number of parallel procedures" in the Salem Unit 1 incident

4.3.3 Human Supervisory Control Complexity Chain

The CSN was organized via a Human Supervisory Control (HSC) complexity chain (Cummings and Tsonis, 2006) (Figure 8). The HSC chain identifies environmental complexity as the objective state of complexity that exists in the world and cognitive complexity as the complexity perceived by a human operator. In the case of a complex environment (NPPs, for example), perceived complexity could be quite high, potentially negatively impacting safe operator performance. For example, many NPPs have redundant systems for safety reasons. However, including a redundant system could double the amount of information available to the operator (including displays and controls), which could increase an operator's cognitive complexity. To mitigate cognitive complexity, organizational policies and procedures along with information representations in the form of interfaces and displays, can be introduced into the system. However, the introduction of these mitigations and devices also can add to the overall perceived complexity of the operator.

In a CSN, organizational complexity represents the additional constraints placed upon the system by operational requirements, such as the number of crewmembers in the control room, emergency procedures, or shift length. The original HSC complexity chain (Figure 8) contained a display complexity category, which considered the complexities offered by visualizations found in displays, including visual, aural, and haptic. This interpretation only recognizes the output to the operator, with no consideration of input from the operator to the system, which is required to close the supervisory control loop. Thus, we propose to change display complexity in the original HSC complexity chain (Cummings & Tsonis, 2006) to interface complexity, to reflect this two-way communication. Interface complexity is the complexity derived from controls and displays, which could include display font size, number of colors used in the display, or numbers and variety of buttons, levers, etc. Figure 9 shows the CSN embedded in the HSC complexity chain.

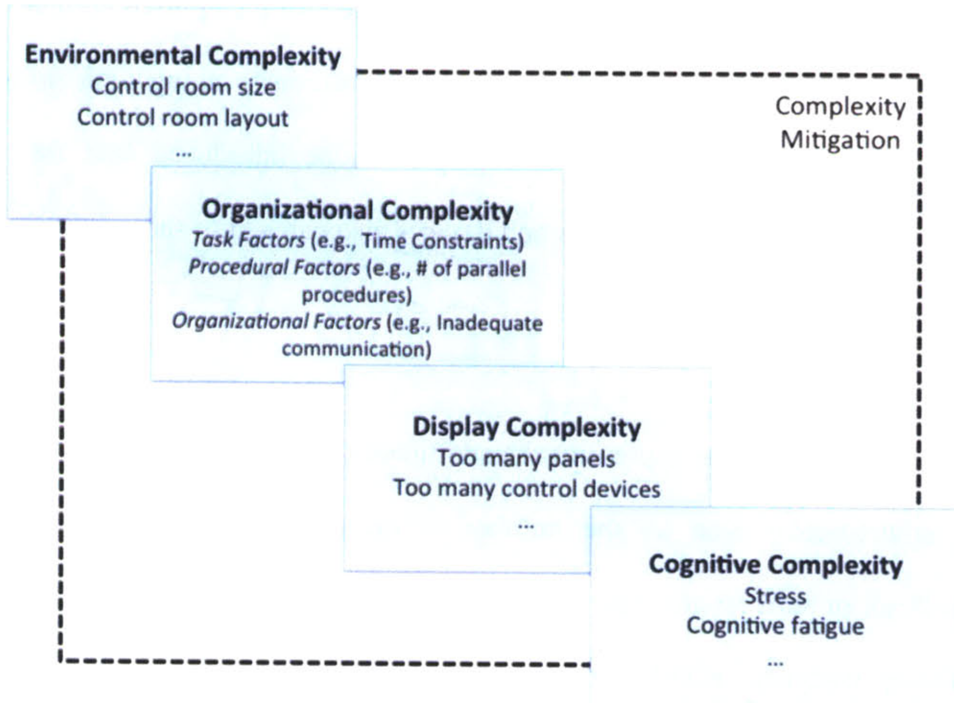


Figure 8. HSC Complexity Chain (modified from Cummings and Tsonis, 2006)

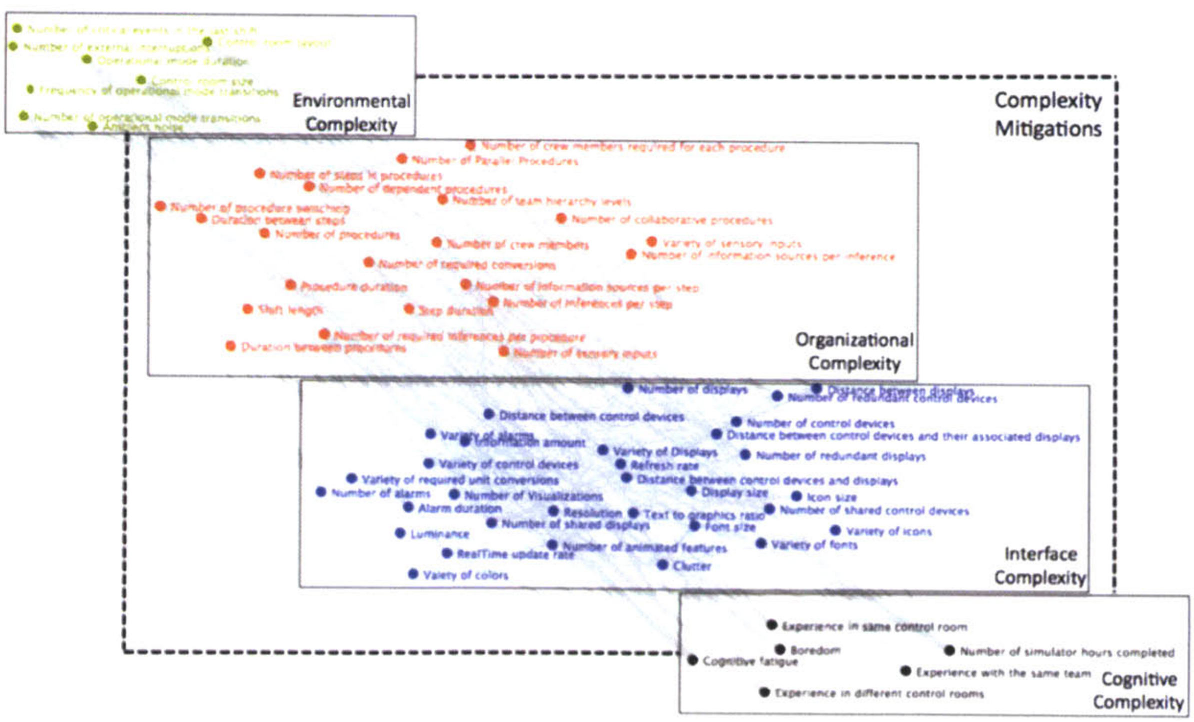
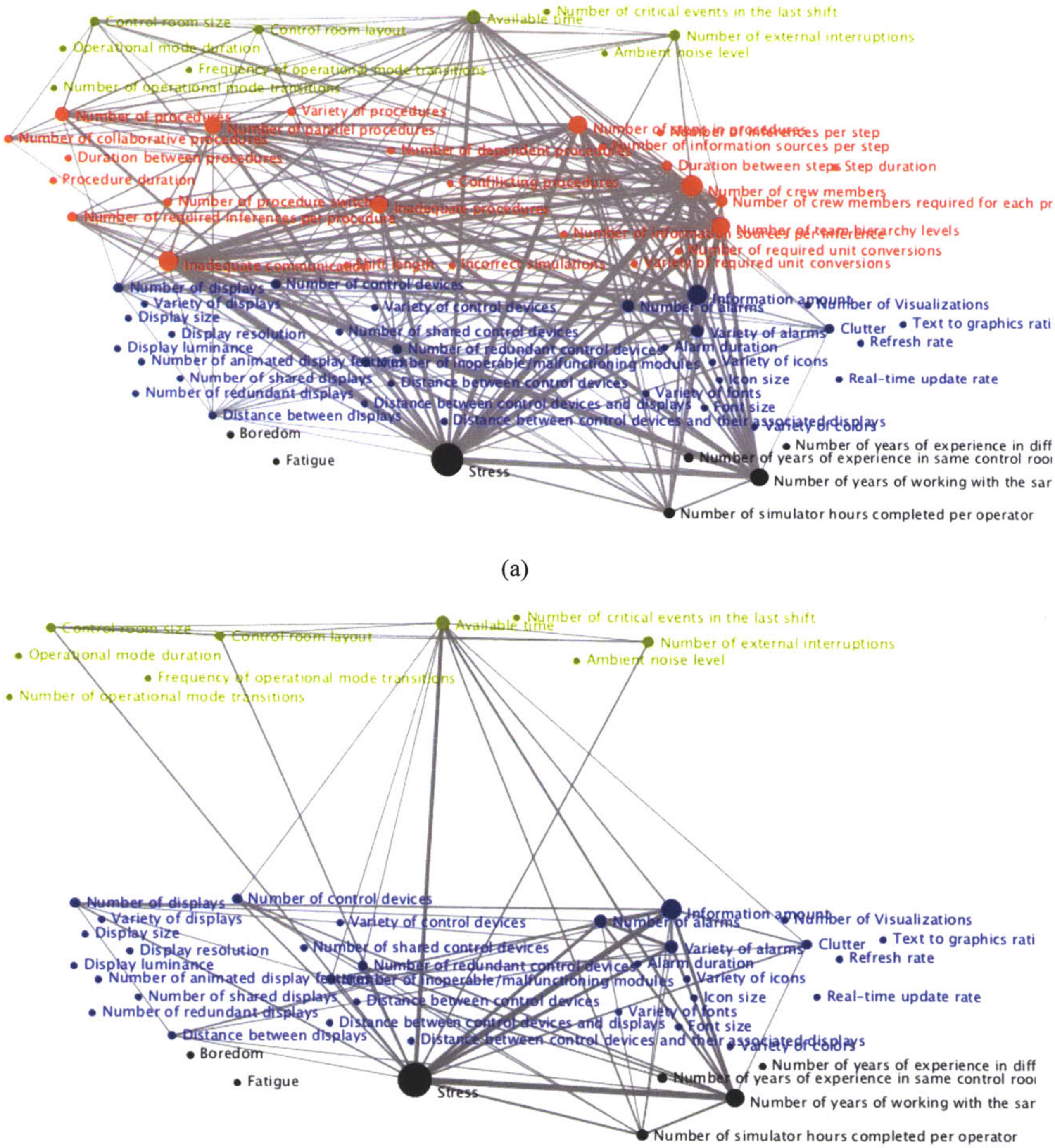


Figure 9. Complexity source network embedded in HSC complexity chain

Using the HSC complexity chain, the effect of different layers of complexity on the overall network can be analyzed. For example, Figure 10 illustrates the effects of removing the organizational complexity layer from the CSN corresponding to North Anna unit 1 incident. Theoretically mitigating organizational complexity sources in this case would reduce the complexity of the network significantly (e.g. a reduction of links from 217 to 57). In addition to providing organizational structure, presenting the network in the HSC complexity chain framework allows researchers the ability to see what sources of complexity are inherent to the system (i.e., environmental), and less likely to be addressed directly as opposed to those sources more easily addressed, such as difficult procedures.

4.3.4 Network Information Visualization and Analysis

Network visualization is an important technique to understand and convey the result of the analysis of networks (Freeman, 2006). A network visualization and analysis tool called CXViz (Complexity Visualization) was developed to visualize the CSNs for all the incidents included in the HERA database. The CXViz interface has 3 main sections (Figure 11): 1) a visualization window that displays the identified sources of complexity within the Human HSC complexity chain (Cummings and Tsonis, 2006), 2) a vertical toolbar that provides several analytic functionalities and visualization tools, and 3) a database window that allows the user to interact with the evidence database. CXViz facilitates the identification of the main contributors to complexity of each CSN (i.e. nodes/links with highest weights and nodes with high number of connections, the so-called node degree). Network theory enables the measurement and evaluation of characteristics of the resulting networks, which allows for comparison of CSNs, identification of emergent patterns, investigation of how the CSNs emerge over time and investigation of aggregate networks. These sections are explained in more detail in Appendix F.



(a)

(b)

Figure 10. A comparison between the North Anna unit 1 incident with (a) and without (b) organizational complexity factors

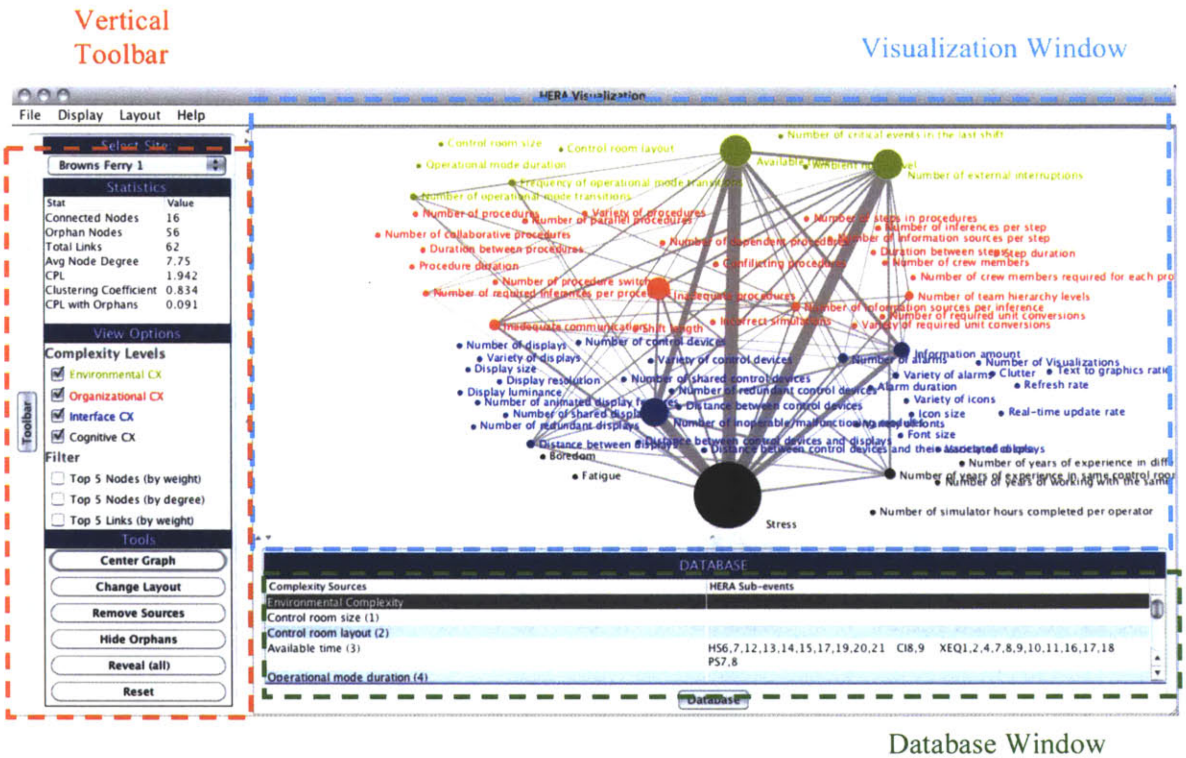


Figure 11. CXViz visualizing the CSN for Browns Ferry unit 1 accident

4.3.5 Network Characteristics

CXViz also provides several important network statistics with regards to complexity that facilitate the network analysis process. The complexity of a network is usually characterized by its non-trivial structure. In particular, "connectivity" can provide insight into the complexity of a network. Connectivity of a network is defined as the ability to find a path from each node to other nodes in the network. Using CSNs as an analytical approach in identifying the interactions between the sources, we propose a reductionist approach to mitigate the propagation effect of interactions between the sources of complexity by reducing the connectivity of the network. The following connectivity metrics are currently measured and reported for each CSN:

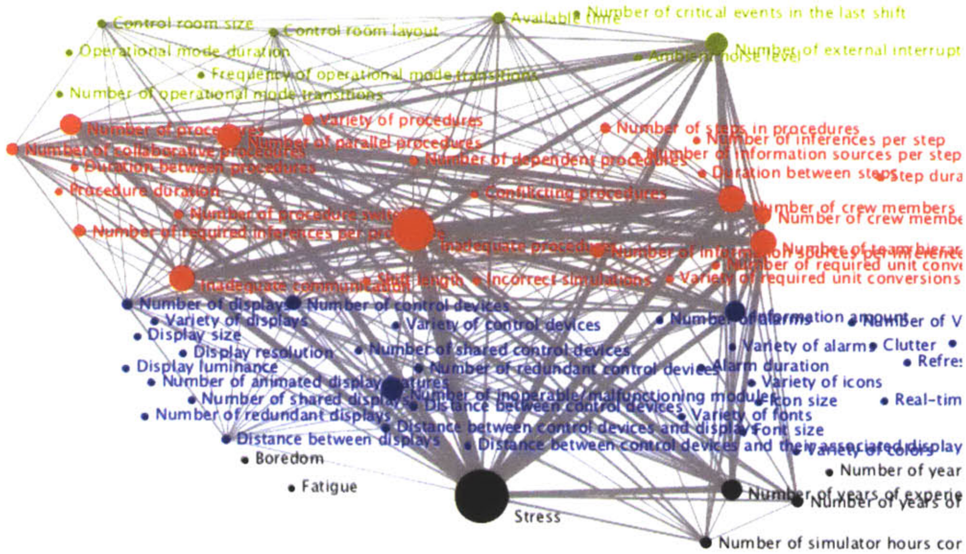
Network Density (ND): ratio of number of links to number of potential links. Network Density is an important measure for connectivity of the network. In the context of CSNs, a smaller density means fewer links and according to Edmonds' (1995) definition of complexity (the number of interconnections could be used as the direct measure of complexity), reducing network density reduces the complexity of the network.

Characteristic Path Length (CPL): CPL is an important measure of network connectivity. It is calculated as the average of all the shortest paths between pairs of nodes. Ideally the CPL of CSNs should be large which means less connectivity is desired (Braha and Bar-Yam, 2004).

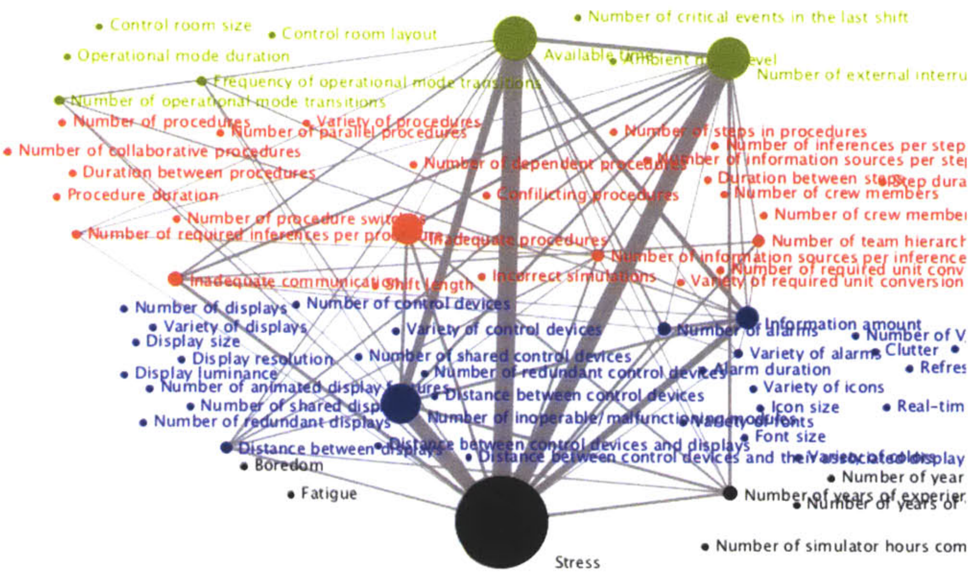
Clustering Coefficient (CC): The total number of actual connections between a node's neighbors over the potential connections between those neighbor nodes. CC is the measure of modularity. Usually a high CC is desirable for systems in which better flow is preferred, however, in order to reduce the connectivity of CSNs, a low CC is desired (Braha and Bar-Yam, 2004).

For example, the network characteristics for two different incidents are analyzed (Figure 12): Salem Unit 1 and Browns Ferry Unit 1. In the Salem Unit 1 incident, complications from river grass intrusion lead to an automatic reactor trip, two automatic safety injections, a manually initiated main steam isolation, and a discretionary declaration of alert. A combination of several unusual events resulted in several human-fault related sub-events and eventually the plant shutdown. On the other hand, in Browns Ferry Unit 1 incident, a candle-induced cable fire in the cable spreading room and Unit 1 reactor building resulted in the reactor shutdown. As shown in Figure 12, Salem 1 CSN is more connected (Higher density, clustering and path lengths) and hence more complex (ND = 0.097; CPL = 0.248 and CC = 0.845) than the Browns Ferry CSN (ND = 0.024; CPL = 0.091; CC = 0.834). Appendix G includes the network statistics for all the incidents contained in HERA.

Another benefit of using CXViz is the ability to work with an aggregate network. The methodology discussed in this section was used to create 22 different CSNs. A synthesized network (i.e., the aggregate network) is created by adding the information from the 22 CSNs into a single network (Figure 13). The aggregate network includes all the possible links from the 22 incidents in HERA. The weight for a node in the aggregate network corresponds to aggregate of weights for that node across the 22 CSNs. Likewise, the weight for each link in the aggregate network corresponds to the aggregate weight of that link across the 22 CSNs. Using the aggregate network, the main contributors to control room complexity as well as important interrelations between them could be identified objectively. The aggregate CSN is explained in more detail in Section 5. A future functionality to be added is allowing the user to determine which networks to aggregate, since a subset of all the networks may be of interest.



(a)



(b)

Figure 12. A comparison between the network characteristics of two CSNs: Salem unit 1 (a) and Browns Ferry unit 1 (b)

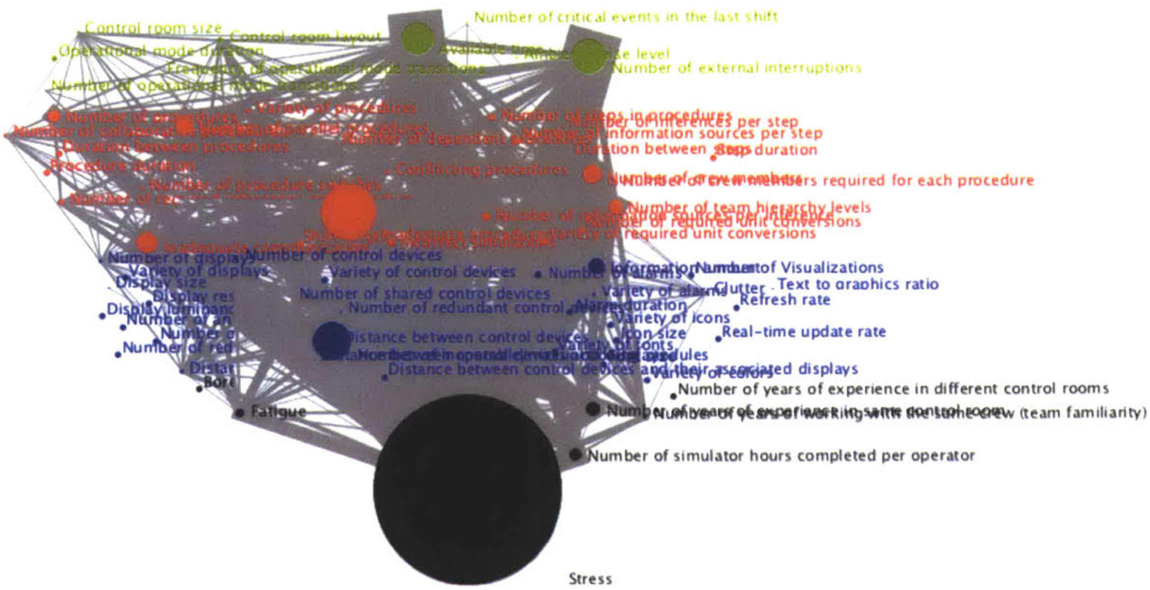


Figure 13. The aggregate CSN for incidents in HERA

This section has presented how objective complexity, defined using the NRC-approved incident databases, can be quantified. As discussed in Chapter 2, one of the limitations of this approach is the influence of the subjective views of the NRC employees involved in preparation of such incident reports. This makes the data from incident reports quasi-objective. However, although there is some subjectivity involved in how these reports are created, the data from incident report databases are arguably a plausible resource to reflect objective reality, or what Babbie (2010) calls the "Agreement Reality", since such reports are subject to significant review and regulatory agency endorsement. On the other hand, subjective complexity is equally important to understand, so that it can be compared against objective complexity and within stakeholder groups. In order to investigate possible stakeholder disparities, subjective complexity data needs to be gathered from different stakeholder groups, and is discussed in the next section.

4.4 Step 4: Subjective Validation

In order to gather subjective complexity views of the stakeholders, a digital survey was developed that allows different groups to rate the identified source, rank the most important sources in terms of their contribution to complexity, and to identify potential interactions between them. Since the survey interview was used as the main method to gather subjective data, the iPad platform was used for its portability and interactivity. The Objective C programming language was used to develop a tool called CXSurvey. Using this tool, stakeholders' opinion on the identified sources of complexity could be gathered. The results of individual surveys are saved in a database and are transformed into CXViz format for further analysis.

4.4.1 Sampling

Due to access limitations, low population (for designers and reviewers), and government regulations such as the Paperwork Reduction Act[3], non-probability sampling methods were used. First, NRC provided a convenience sample for operators and NRC reviewers. Next, snowball sampling was used to identify control room designers. Several companies such as GE, Westinghouse, Mitsubishi, Toshiba, A&W and Areva were contacted and referrals were made. Overall, 8 designers, 3 reviewers and 16 operators were interviewed.

4.4.2 Procedure

Using CXSurvey, the interviewees were first asked to review a consent form (Appendix H), and then they were asked to provide their demographic information. Next, the interviewees reviewed,

[3] http://www.archives.gov/federal-register/laws/paperwork-reduction/

rated (section 4.4.2.1) and ranked (section 4.4.2.2) the identified sources and updated the list if necessary. Next, a unique CSN appeared based on the ratings provided, and the interviewees were asked to identify important interactions (links) between such sources that they perceived as contributing to accidents or job difficulties (section 4.4.2.3). The resultant CSN then feeds into CXViz for further analysis. Lastly, each interviewee answered a series of open-ended questions regarding sources of complexity and potential complexity mitigations (section 4.4.2.4). A post-survey interview was conducted to understand the rationale behind specific choices made during the survey.

4.4.2.1 Complexity Source Rating

In this part, interviewees were asked to rate all the previously identified sources of complexity on a 5-point Likert scale (1 - "Strongly Disagree, 2 - "Disagree, 3 - "Neither Agree nor Disagree, 4 - "Agree", and 5 - "Strongly Agree"). An "N/A" option was provided to let the interviewee identify the sources that are not relevant to complexity of NPP control room environments (Figure 14) Additional definitions and examples were provided for each source to clarify their meaning in the NPP control room context. The wording of sources was slightly modified to facilitate their comprehension. In addition, several sources that were not supported by HERA incident were removed. A pilot study was conducted using two NRC ex-operators and one NRC reviewer, the result of which informed the wording of sources (see Appendix B.3 for the list of sources). In order to improve the comprehensibility of this part and to manage the level of cognitive effort required to compare different sources, six different categories of sources were used (see Table 3 for a list of these categories and their definitions). To facilitate grouping and to improve the recognition of different categories, each category was developed on a different page with a unique background color.

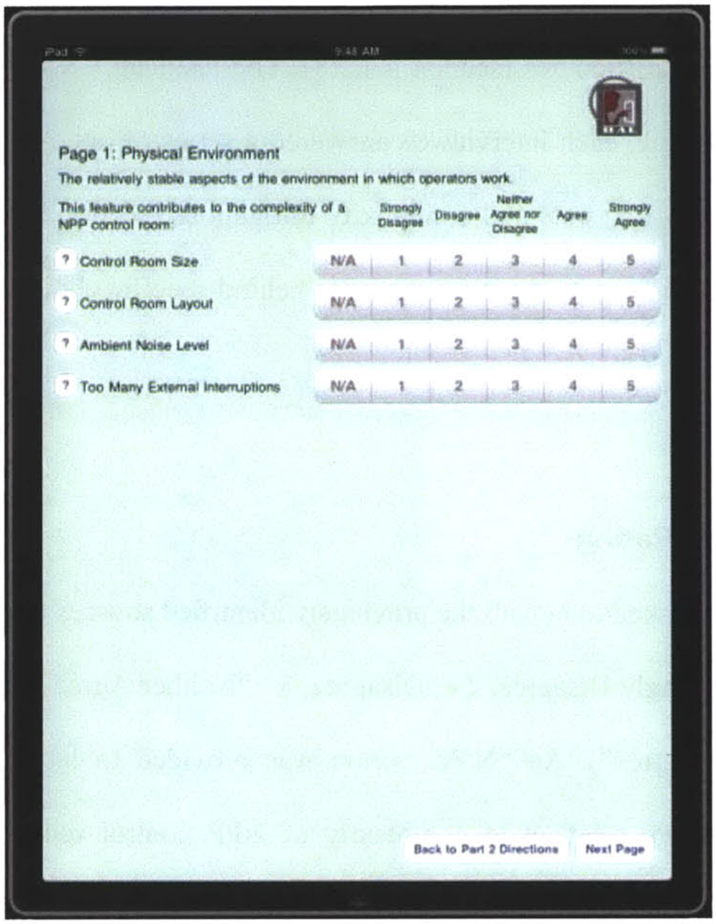


Figure 14. Complexity source rating for the physical environment

Table 3. Complexity source categories

Complexity Category	Definition
Physical Environment	The relatively stable aspects of the environment in which operators work
Task Factors	Factors dictated by the state of the plant
Procedural Factors	Procedural factors used to retain/return the plant to the desired state.
Organizational Factors	Factors determined by organizational rules, regulations and processes.
Human System Interface (HSI)	The components of the control room with which operators must interact in order to control, monitor, and interact with the system.
Cognitive Factors	Those cognitive factors unique to individual operators

4.4.2.2 Complexity Source Ranking

In this part, the interviewees ranked the sources of complexity that they thought contributed the most to complexity of the NPP control rooms. This part has two pages. On the first page, the interviewee chooses the top 5 sources in terms of contribution to complexity of the NPP control rooms from the list of sources that were rated 4 or 5 in part 2. On the second page, the interviewee is asked to rank the top 5 sources they choose on the first page (Figure 15).

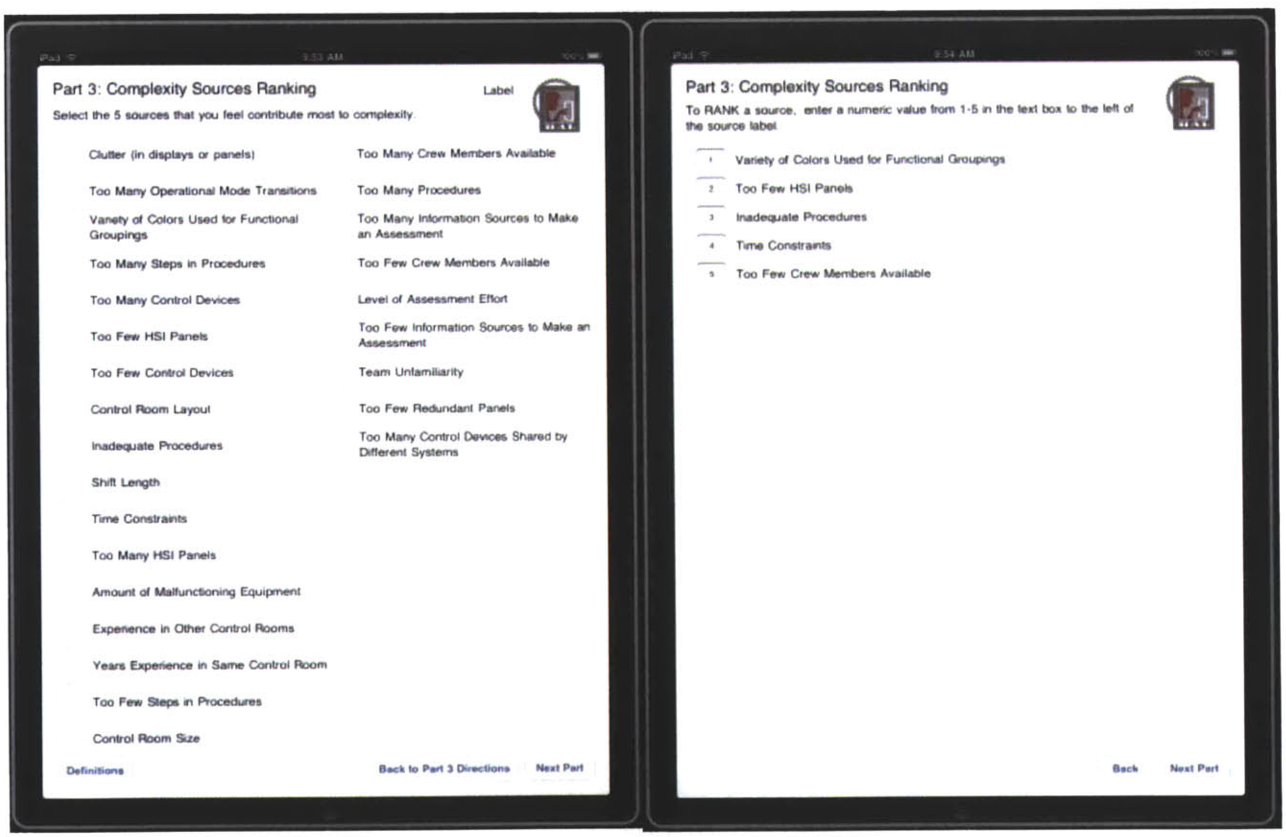


Figure 15. Complexity source ranking. Choosing top 5 (left) and Ranking the top 5 (right)

4.4.2.3 Identifying Interactions

In this part, interviewees were asked to identify the interactions between the identified sources of complexity. First, an explanation was provided to prepare each interviewee for this section (see

Appendix I). Next, based on their source ratings, the interviewees viewed a complexity source network emerging in a circular format (Figure 16). Interviewees then interacted with the interface to rotate the network and were asked to identify pairwise links between nodes in terms of their combination of effects in an incident. After a link was created, the interviewee was asked to choose a weight on a 5-point scale for the link in terms of importance of contribution. Interviewees are asked to identify 5 or more links.

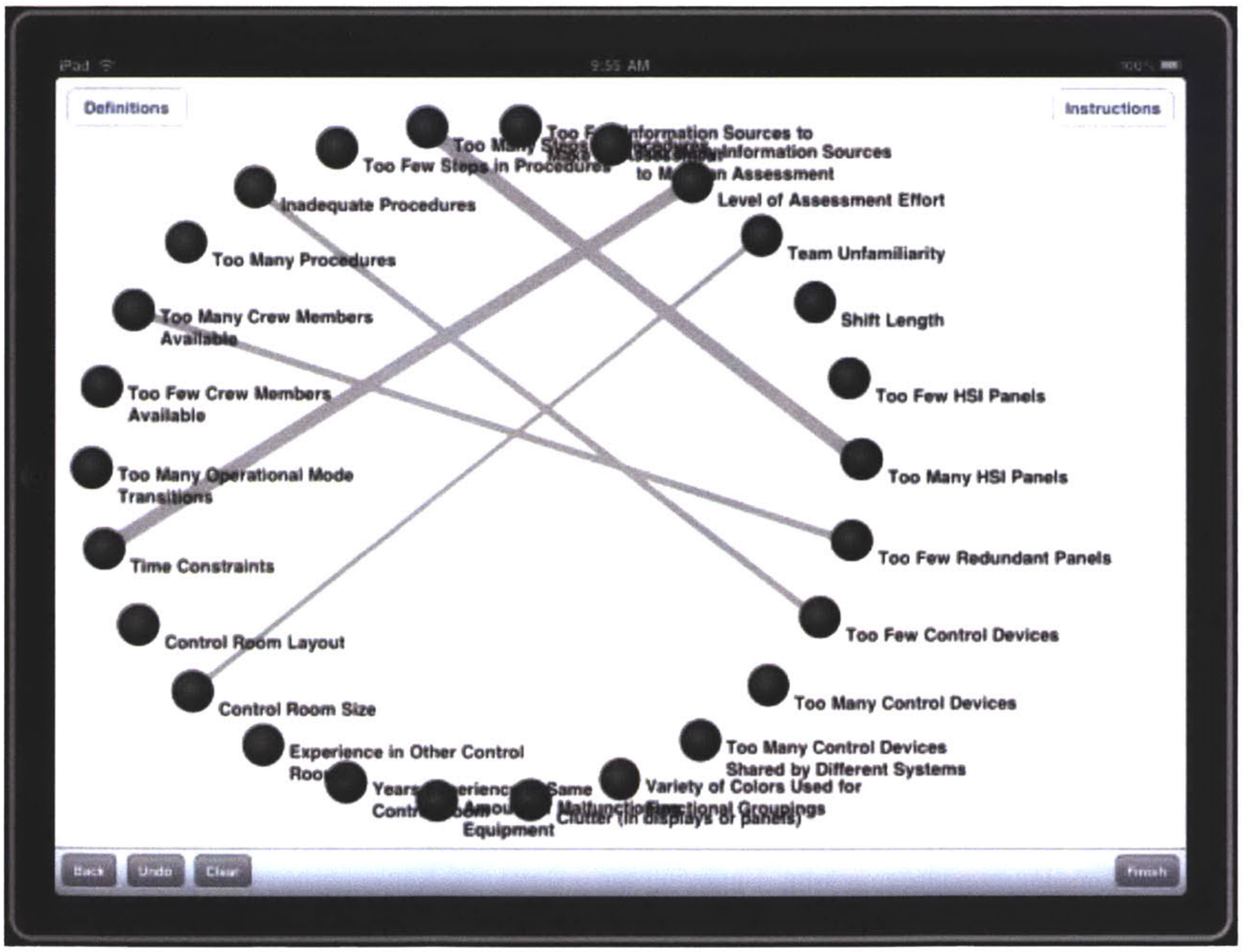


Figure 16. An example CSN for choosing complexity source interactions

4.4.2.4 The Open-ended Questions

In the last part of the survey, the interviewees responded to a series of open-ended questions (see Appendix I). First the interviewees were asked to identify other potential sources of complexity. Next, they were asked to suggest potential complexity mitigations techniques. Lastly, they were asked to provide any additional feedback or comments.

4.5 Step 5: Objective-Subjective and Stakeholder Views Variations

The ranking information, described in Section 4.4.2.2, was then compared to the top 5 objective sources with the highest number of evidences (i.e., most common sources) to ensure that complexity views of the stakeholders are aligned with the objective reality of the incidents included in HERA. In addition, the source rating information, discussed in Section 4.4.2.1 was used to compare different stakeholder groups in terms of their views on specific sources of complexity.

In conclusion, this chapter introduced the first 4 steps of a 5-step methodology to address the research questions raised in Chapter 3. Step 1: a list of sources of complexity was produced using a combination of methods. Step 2: content analysis was used to find objectively evidence for the identified sources in 22 previous incidents included in the HERA database. An evidence database was created and was used as the basis for the objective validation of sources Step 3: potential interactions between the identified sources were identified and represented via the complexity source networks. Step 4: subjective views of the operators, designers, and NRC reviewers on the identified sources were collected using the survey-interview method. Step 5 (discussed in the next Chapter): the objective evidence from the HERA database was compared to the subjective views of the stakeholders to identify potential variations. In addition, the subjective views of different stakeholder groups (e.g., Designers, Operator, and Reviewers) were compared to identify potential differences in their views on the identified sources. The next chapter discusses the result of these comparisons.

5. RESULTS

In order to address the research questions described in Chapter 3, an analysis was conducted on the evidence obtained using the content analysis of the HERA database and the subjective complexity views gathered using the survey-interview. This chapter highlights the results of this analysis.

5.1 Most Contributing Sources of Perceived Complexity

Using the evidence-based approach discussed in Chapter 4, the main contributors to perceived complexity in 22 incidents in HERA were identified. In particular, two different rankings were developed: the most *frequent* sources and the most *connected* sources.

5.1.1 Most Frequent Sources

The most frequent sources are the sources for which the most number of evidences were found in the HERA evidence database. As discussed in Chapter 4, whenever a source was found to be a contributor to a single sub-event in a particular incident in HERA, the sub-event code associated with that sub-event was collected as the evidence to support the existence of the source. The ranking of the most recurring sources was created with regards to the number of evidences in the HERA evidence database (Table 4). In other words, sources with large number of evidences were identified as contributor to the perceived complexity of the operator(s) in different sub-event more frequently.

Table 4. Ranking of the most supported sources

Ranking	Source	Number of Evidences
1	Stress	591
2	Inadequate procedures	180
3	Available time	94
4	Number of external interruptions	87
5	Number of inoperable modules	83
6	Inadequate communication	65
7	Number of parallel procedures	53
8	Number of crew members	47
9	Number of years of experience in same control room	45
10	Information amount	40
11	Number of procedures, Number of team hierarchy levels	38
12	Number of simulator hours completed per operator	37
13	Number of malfunctioning modules	36
14	Incorrect simulations, Number of alarms	20
15	Number of steps in procedures	19
16	Fatigue, Number of information sources per inference	17
17	Control room layout	15
18	Number of required inferences per procedure	13
19	Conflicting procedures, Number of years of working with the same crew (team familiarity), Variety of procedures	11
20	Number of control devices, Number of crew members required for each procedure	9
21	Distance between displays, Variety of alarms	8
22	Number of collaborative procedures, Number of procedure switches	7
23	Number of displays	5
24	Ambient noise level, Clutter, Number of redundant control devices	4
25	Control room size, Number of inferences per step	3
26	Duration between steps, Frequency of operational mode transitions, Number of critical events in the last shift, Number of dependent procedures, Number of operational mode transitions, Number of shared control devices	2
27	Display size, Distance between control devices, Distance between control devices and displays	1

According to these results, stress was identified as the main contributor to the perceived complexity in 591 sub-events, which accounts for 35% of the total number of evidences (1674). This high node-weight contribution explains the large size of the node corresponding to stress in the aggregate CSN (Figure 17). Inadequate procedures were the second largely supported source for being the contributor in 180 sub-events, which accounts for almost 11% of the total number of evidences. Available time, number of external interruptions and number of inoperable modules were also well supported with 94, 87 and 84 evidences accordingly. Appendix L includes the node-weight contributions for sources. In addition, no evidence was found for 28 sources listed in Table 5. The majority of such sources are related to digital interface or display components of the control room (e.g., font size, number of icons, etc.) and were identified by the subject matter experts with the advanced digital control rooms in mind. Unfortunately, since most of the incidents analyzed in HERA have occurred in the 1970s and 1980s, such digital components were absent from the control rooms under investigation.

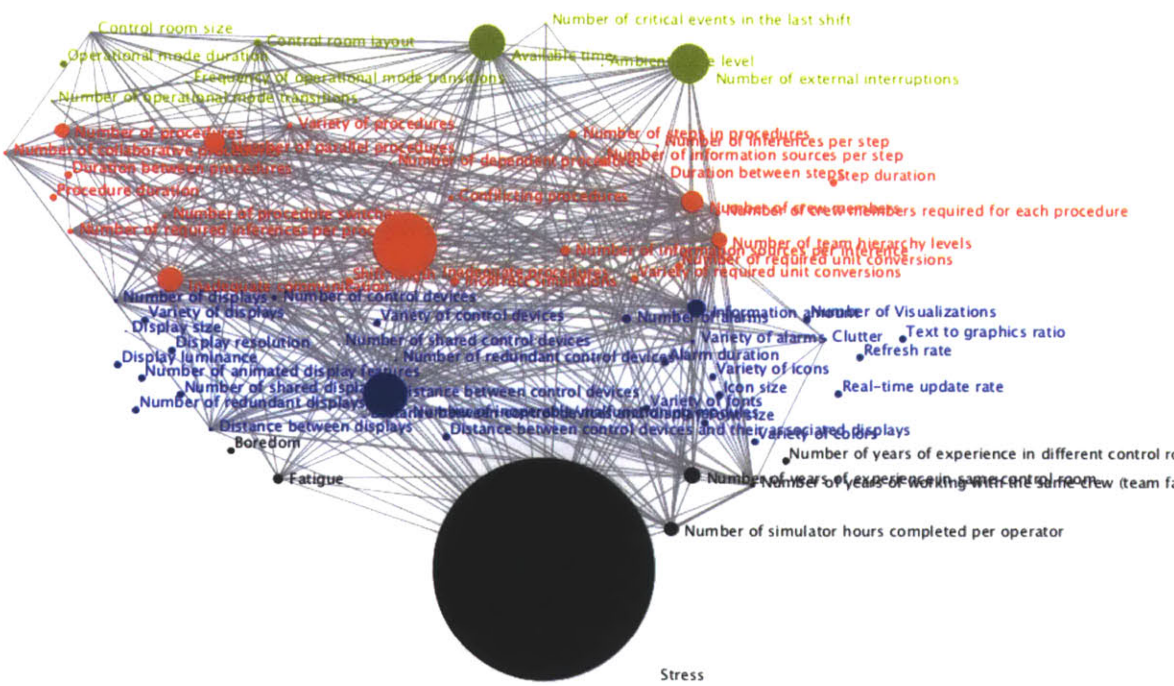


Figure 17. Stress in the aggregate CSN

Table 5. Sources for which no evidence was found in HERA

Environmental Complexity • Operational mode duration **Organizational Complexity** • Duration between procedures • Duration of procedures • Number of information sources per step • Duration of steps • Number of required unit conversions • Variety of required unit conversions • Shift length **Cognitive Complexity** • Boredom • Number of years of experience in different control rooms	**Interface Complexity** • Alarm duration • Display luminance • Display resolution • Distance between controls and their associated displays • Font size • Icon size • Number of animated display features • Number of redundant displays • Number of shared displays • Number of visualizations • Real-time update rate • Refresh rate • Text to graphics ratio • Variety of colors • Variety of control devices • Variety of displays • Variety of fonts • Variety of icons

5.1.2 Most Connected Sources

As discussed in section 4.3, when presenting an incident using a complexity source network, interactive complexity of the incident could be shown as links between the sources (nodes). In that sense, the number of links to a source (node degree) can be considered an important indicator of importance. Table 6 lists the ranking of sources by degree or number of connections. According to these results, stress is the most connected source in the aggregate CSN with 41 links followed by information amount, inadequate procedures and available time with 36, 35, and 34 links accordingly. Although the number of connections in the degree ranking is close in compare to the number of evidences in the weight ranking, generally the majority of the rankings agree in both lists. Intuitively, the more supported (by evidence) sources are also the most connected. These so called orphan nodes are essentially the same sources for which no evidence was found in HERA. Since the majority of these sources are sources related to interfaces or displays, the lack of evidence in the incidents included in HERA that occurred in the 1970s and 1980s is not surprising.

5.2 Objective Evidence vs. Subjective Complexity Views

Using the data provided by the HERA content analysis (objective evidence) and survey-interview of the stakeholders (subjective views) discussed in Chapter 4, the objective-subjective comparison (research question 2) can be accomplished. One of the main limitations of this study is access to stakeholders. Overall, a convenient sample of 8 designers, 16 operators and 3 reviewers identified 20, 7, and 10 distinct sources in their top 5 rankings. Also as shown in Table 4 and Appendix L, the top 5 sources in the node-weight ranking account for almost 64% of total number of evidences found in HERA. Therefore, the non-identification of these sources by stakeholder groups may support the hypothesis that there are large variations between complexity views of the stakeholders and the objective reality of previous incidents in HERA.

Table 6. Ranking of the most connected sources

Ranking	Source	Number of Connections
1	Stress	41
2	Information amount	36
3	Inadequate procedures	35
4	Available time	34
5	Number of available crew	33
6	Number of parallel procedures	32
7	Inadequate communications, Number of team hierarchy levels, Number of inoperable/malfunctioning modules	31
8	Number of control devices	30
9	Number of displays	29
10	Number of external interruptions. Distance between displays	27
11	Number of procedures, Number of crew members required for each procedure	25
12	Number of steps in a procedure, Number of information sources per inference	24
13	Number of years of experience in the same control room	23
14	Number of alarms	22
15	Number of steps in procedures	21
16	Variety of procedures, Number of required inferences per procedure	19
17	Variety of alarms	18
18	Clutter, Team familiarity	17
19	Number of procedure switches, Number of simulator hours completed	16
20	Distance between control devices and displays	14
21	Duration between steps, Distance between control devices	13
22	Number of dependent procedure, Incorrect simulation	11
23	Number of redundant control devices, Cognitive fatigue	10
24	Number of operational mode transitions, Frequency of operational mode transitions, Control room size	5
25	Conflicting procedures	4
26	Control room layout, Number of critical events during the past shift	3
27	Number of inferences per step, Number of shared control devices	2
28	Display size, Variety of control devices	1

For the purposes of this preliminary investigation, the top 5 most supported sources were compared to the top 5 selection of each stakeholder group (see Appendix K for a complete comparison of all the sources identified in the top 5 selection of stakeholders and the objective sources). A weighting system was used to create the aggregate top 5 for each stakeholder group. First the following weights were assigned to the ranking list of each interviewee: 5 for the first rank, 4 for the second rank, 3 for the third rank, 2 for the fourth rank and 1 for the fifth rank. Next, all the entries from the interviewees within a stakeholder group was listed and the weights for common sources were added together. In case of a tie, the number of appearance in different rankings was used. Finally, the top 5 sources with highest weights were selected. Table 7 lists the top 5 selections for different stakeholder groups in compare to the objective top 5 sources from Table 6. Appendix K lists the full list of sources included in the top 5 selections of different stakeholder groups.

According to these results, out of the three groups, reviewers were more in line with the objective representation of HERA. Reviewers identified 4 of the top 5 objectively supported sources. This result is not surprising since NRC employees were more familiar with the past incidents and were potentially familiar with HERA. On the other hand, Operators identified only two of the top 5 sources. Designers did not find any of the objective top 5 sources. This result might indicate that designers' views on complexity are somewhat unrealistic in compare to the objective representation of HERA or at least doesn't acknowledge some of the recurring complexity sources that contributed to the previous incidents under investigation. Since the top 5 objective sources were heavily supported by the evidence, and hence, contributed many times to past incidents, non-acknowledgement of the importance of such sources might indicate a gap in systematic learning from previous accidents. Although this result is important, the significance of the chosen sources by each group should be also assessed.

Table 7. Top 5 selections of stakeholder groups vs. the objective top 5. The sources in agreement with the objective top 5 are shown in green

Objective	Designers	Reviewers	Operators
1. Stress	1. Too Many Information Sources to Make and Assessment	**1. Time Constraints**	**1. Amount of Malfunctioning Equipment**
2. Inadequate Procedures	2. Number of Concurrently Used Procedures	**2. Inaccurate Simulator Training**	2. Volume of Information
3. Number of Inoperable Modules/Malfunctioning Modules	3. Level of Assessment Effort	3. Too Many Alarms	3. Too Many Alarms
4. Time Constraints	4. Too Many Procedures	**4. Too Many External Interruptions**	**4. Too Many External Interruption**
5. Number of External Interruptions	5. Time Constraints	**5. Stress**	5. Inadequate Communication

In order to evaluate the importance of identified sources in each group in compare to the available evidence, the node-weight contribution of stakeholder group selections were calculated. First, the percentage of contribution of each source was calculated as the weight of the source (the number of evidences found to support it) divided by the sum of all the source weights. For example the percentage of contribution of "Number of Malfunctioning Modules" was calculated as 36 (weight of the source or the number of evidences found for the source)/1674 (sum of all the evidences) = 2.15% (see Appendix J for node-weight contribution of all the sources). According to this calculation, the top 5 objective sources account for 64% of the overall evidence derived from the incident report databases. Next, the percentage of contribution for stakeholders' top 5 sources was calculated and the overall contribution was compared with the objective top 5 sources (Figure 18).

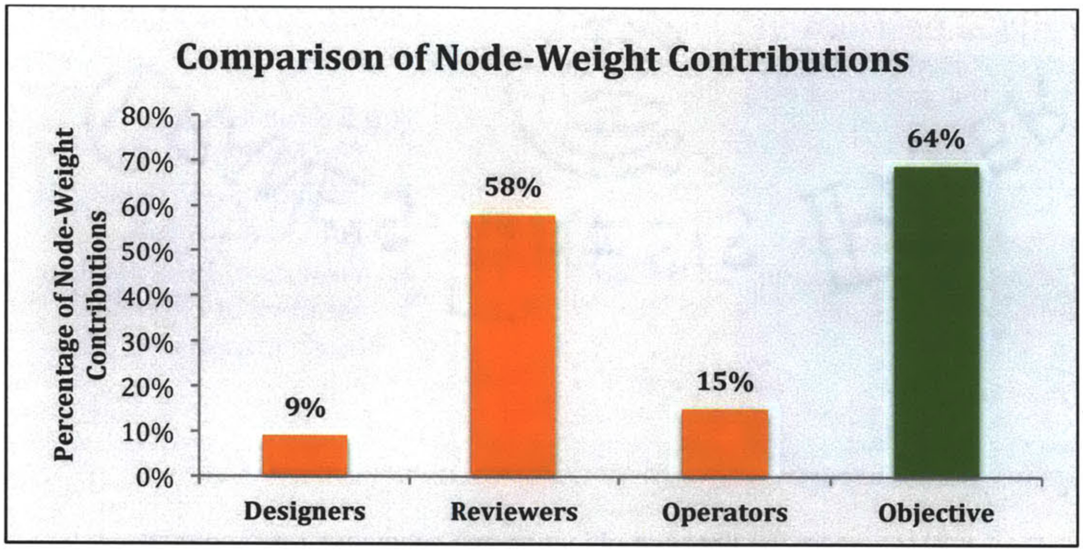


Figure 18. A comparison of different stakeholder groups' top 5 selections and the objective top 5 in terms of percentage of node-weight contribution

The results show a high agreement between reviewers' views on complexity and the objective complexity data. The top 5 sources ranked by the Reviewers reflect 57.77% of the overall evidence derived from the incident report databases. Designers not only did not acknowledge any of the objective top 5 sources, but also their identified source weights reflect only 8.91% of the objective evidence. Finally, although operators acknowledged two of the objective top 5 sources, the top 5 sources they thought contributed the most to perceived complexity account for only 15% of the total number of evidences.

The same weighting system (5-4-3-2-1) was used on the top 5 sources derived in the previous step for each stakeholder group to get the overall subjective top 5. Figure 19 shows the comparison between the top 5 subjective and the top 5 objective sources.

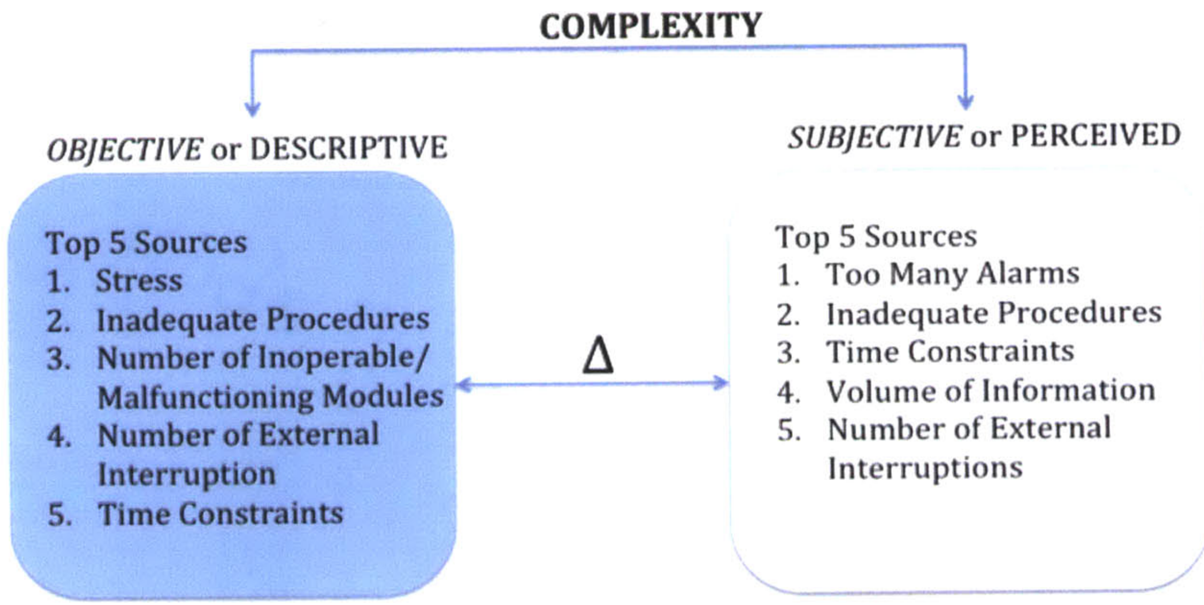


Figure 19. Comparison between objective and subjective top 5 sources

According to these results, overall the aggregated stakeholder views on complexity agree with the majority of the objective evidence from the 22 incidents analyzed in the HERA database. Aggregate stakeholders' top 5 sources include 3 of the objective top 5 sources. However, the top 5 subjective sources only account for 25.15% of overall number of evidences found in HERA, whereas, the top 5 objective sources reflect 63.98% of the evidences. In addition, the current approach doesn't take the difference between the stakeholder groups into account and assumes an agreement among operators, designers and reviewers. This assumption will be checked in section 5.4.

5.3 The Effects of Removing Stress

The content analysis of HERA revealed that Stress contributed the most to subjective complexity of NPP control rooms in the 22 incidents under investigation. 591 evidences were found for stress, which stands for 35.30% of total number of evidences (1674). However, Stress is also a controversial choice as a source of complexity. Although stress could be considered a source of complexity, it could also be the effect of complexity in a causal manner. For that reason, performing the analysis without stress could be insightful.

Stress was replaced by the next highest ranked source "Inadequate Communication" in the objective top 5 as the 5^{th} most supported source. Table 8 shows the updated node-weight contribution of the objective top 5 sources (without stress) and subjective stakeholder top 5 selections. Using the same weighting system discussed in the previous section, the updated percentages of contribution without stress were calculated and the different groups were compared as shown in Figure 20. Without stress, reviewers' agreement with the objective top 5 was reduced from 4 sources to 3 and the operators' agreement was improved from 2 sources to 3. Designers are still the group with the most mismatched complexity views. They did not identify any of the objective top 5 sources. In terms of node-weight contribution of the sources chosen by different groups, designers were the worst group with 13.85% agreement with the objective data. Reviewers and Researchers' top 5 sources more closely matched the objective top 5 with 36% and 23% contribution respectively. According to this result, although the percentage of node-weight contribution is slightly improved for operators and designers, there are still large variations between these views and the objective evidence.

Table 8. Top 5 selections of different stakeholder groups without stress

Objective	Designers	Reviewers	Operators
1. Inadequate Procedures	1. Too Many Information Sources to Make and Assessment	**1. Time Constraints**	**1. Amount of Malfunctioning Equipment**
2. Number of Inoperable Modules/Malfunctio ning Modules	2. Number of Concurrently Used Procedures	**2. Inaccurate Simulator Training**	2. Volume of Information
3. Time Constraints	3. Level of Assessment Effort	3. Too Many Alarms	3. Too Many Alarms
4. Number of External Interruptions	4. Too Many Procedures	**4. Too Many External Interruptions**	**4. Too Many External Interruption**
5. Inadequate Communication	5. Time Constraints	5. Cognitive Fatigue	**5. Inadequate Communication**

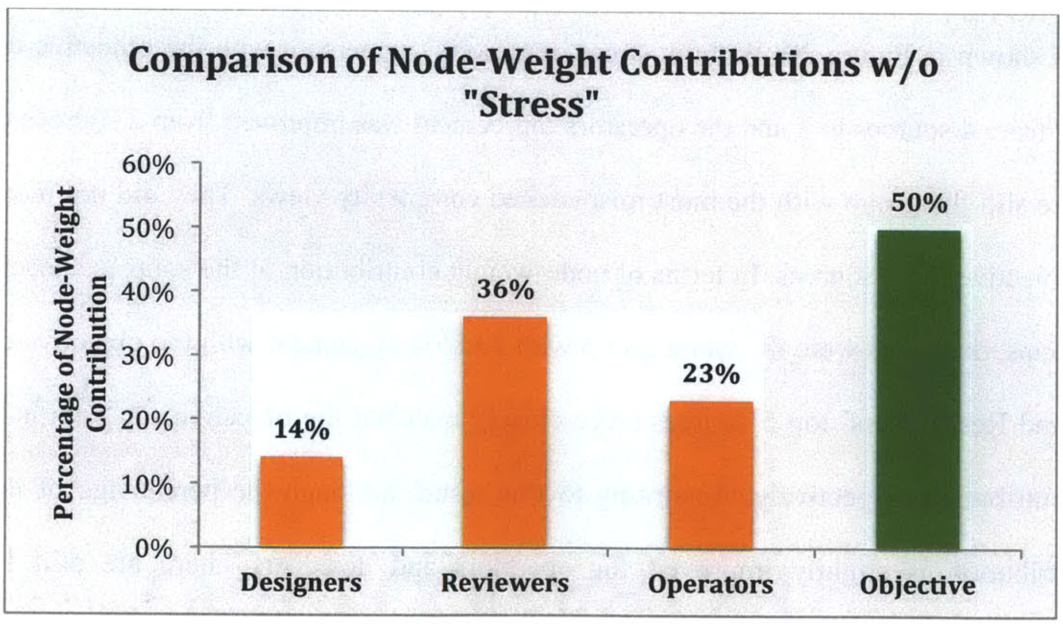


Figure 20. Percentage of agreement of the stakeholders' top 5 selections with the objective top 5

5.4 Stakeholder Complexity Views

5.4.1 Descriptive analysis of source ratings

As discussed in Chapter 5, each stakeholder was asked to rate the identified sources on a 5-point Likert scale. The responses were coded by assigning a numerical value to each. In the survey, respondents were asked how much they agree or disagree with the contribution of 54 sources to perceived complexity in NPP operations. The response categories were strongly agree, agree, neither agree or disagree, disagree, strongly disagree, and not applicable. The responses were coded as follows: not applicable = 0, strongly disagree = 1, disagree = 2, undecided = 3, agree = 4, and strongly agree = 5. These data were entered on an Excel spreadsheet for analysis.

First, a descriptive analysis of the rating data was conducted in which the most frequent rating (mode) for each source was identified (see Appendix M). This result showed that the majority of stakeholders agreed with the majority of sources (i.e., on average, the stakeholders chose the rating of 4 for 75% of the sources). In addition, "Cognitive fatigue" and "Conflicting procedures" were rated 5 (strongly agree) by the majority of the stakeholders. Table 9 lists the sources for which the majority of the stakeholders gave the rating of 0-3.

Finally, to simplify the results, a general agreement/disagreement analysis as suggested by Trochim (2000) and others was conducted for different categories of factors listed in Table 3. First, the two response categories, "strongly agree (5)" and "agree (4)" were combined into a single nominal category called "agree". Likewise, the two response categories "strongly disagree (1), and "disagree (2) were combined into the nominal category "disagree". Figures 21-27 depict the range of responses visually with bar charts that display the number of respondents who expressed agreement, disagreement, or undecided, with physical environment factors, task factors, procedural factors, organizational factors, human system interface factors, and cognitive factors respectively.

Table 9. Sources that were rated 0-3

Rating	**Source**
Not Applicable (0)	• Too few control devices shared by different system
Strongly Disagree (1)	None
Disagree (2)	• Too many operational mode transitions • Frequency of operational mode transitions • Amount of required unit conversions • Variety of procedures • Too few steps in a procedure • Too few crew members to execute the procedure • Too few redundant panels • Too few control devices • Too few redundant control devices • Too many redundant control devices • Too many information sources to make an assessment
Neither Agree or Disagree (3)	• Control room size • Too many items on turnover sheets • Panel too small • Panel too large

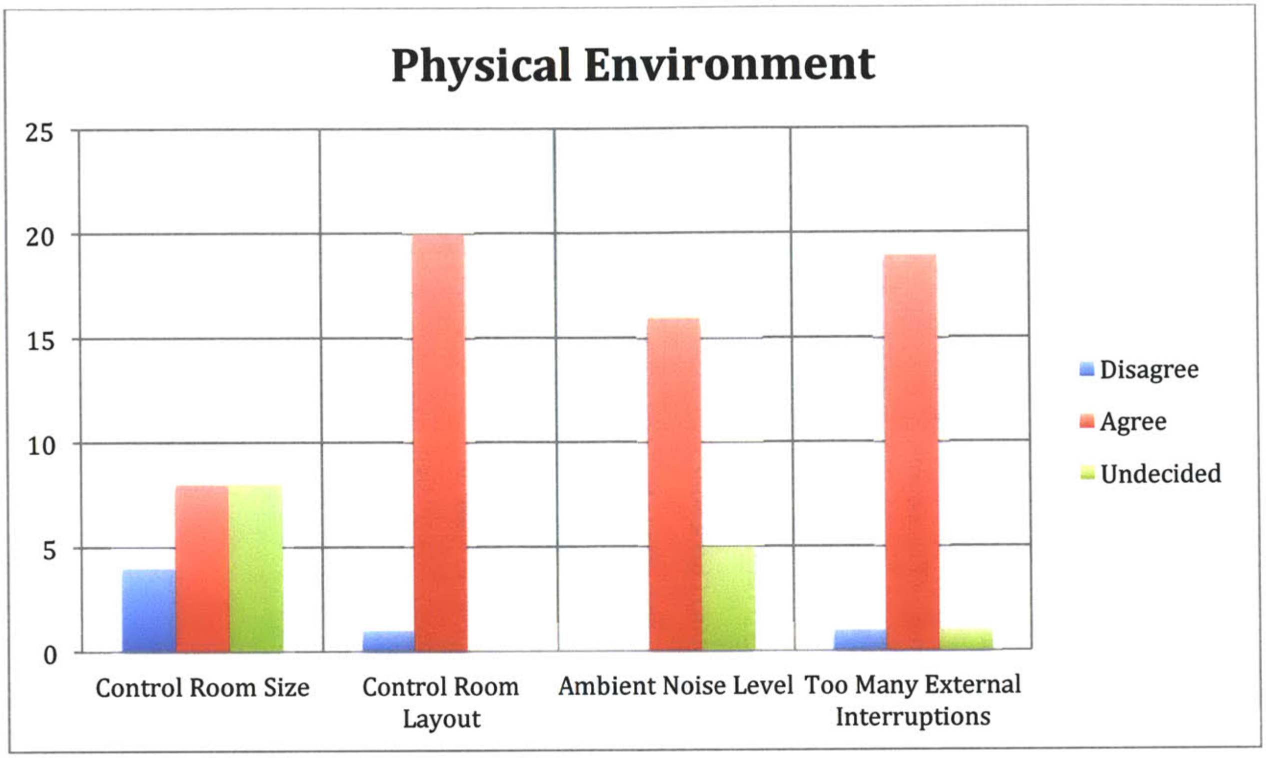


Figure 21. Ratings for physical environment factors

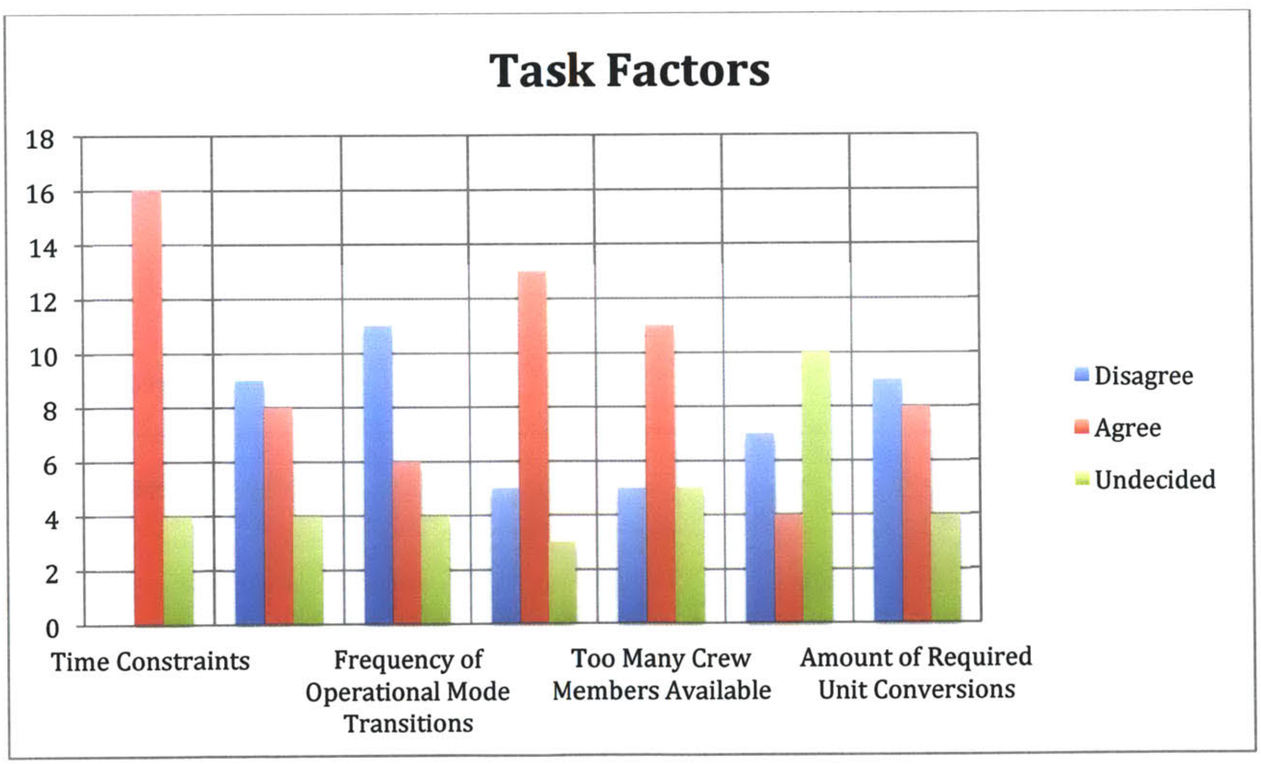


Figure 22. Ratings for task factors

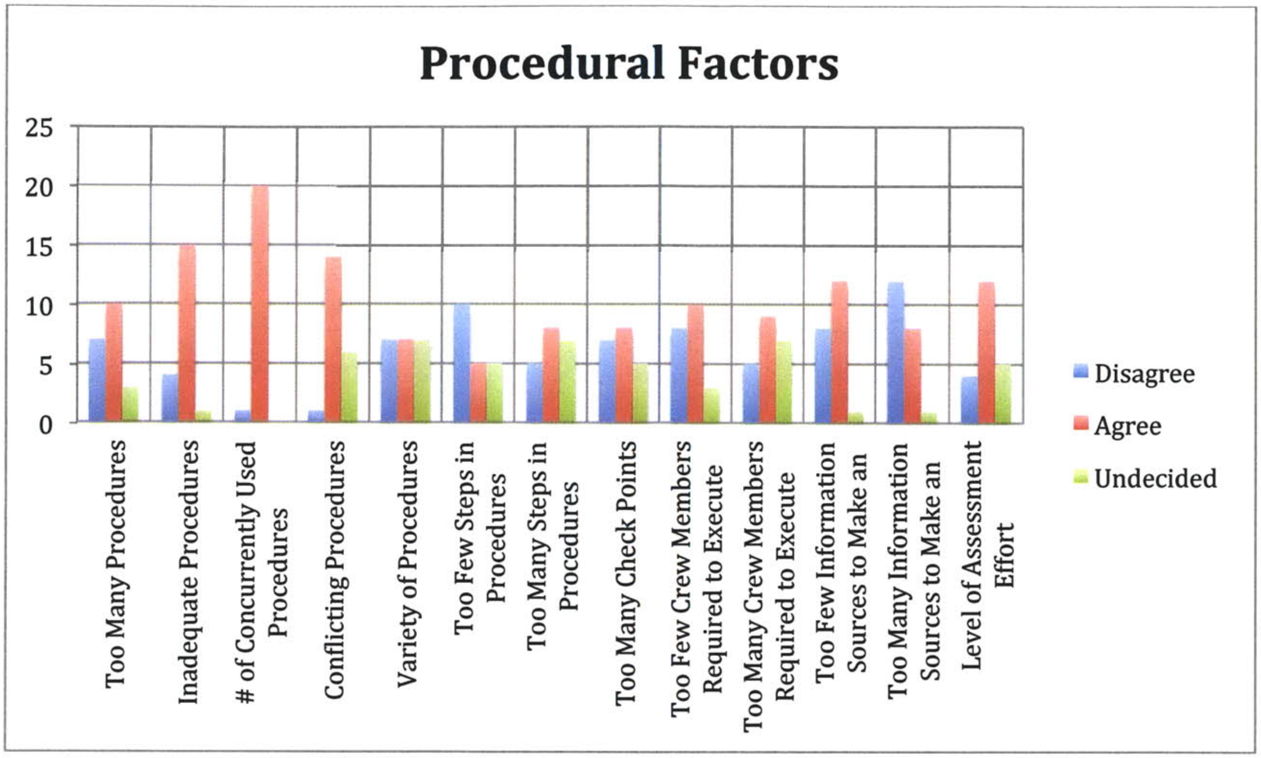


Figure 23. Ratings for procedural factors

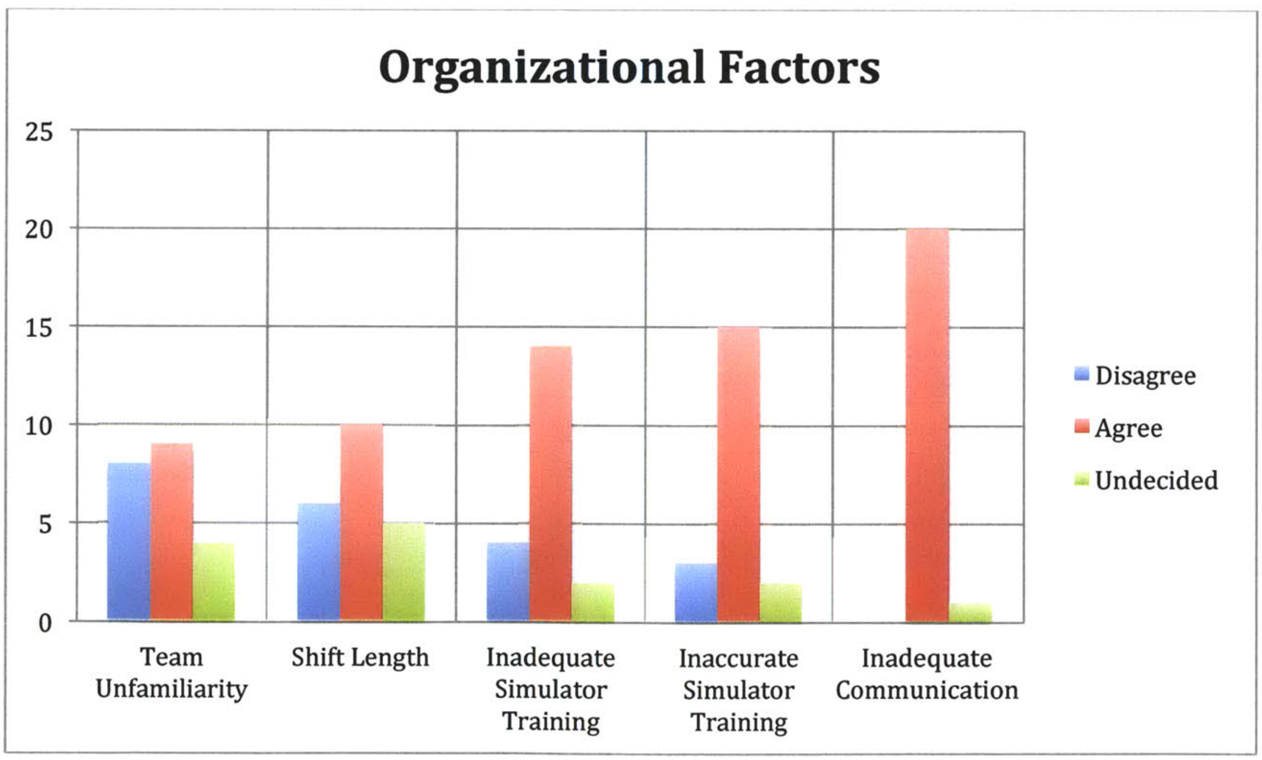


Figure 24. Ratings for organizational factors

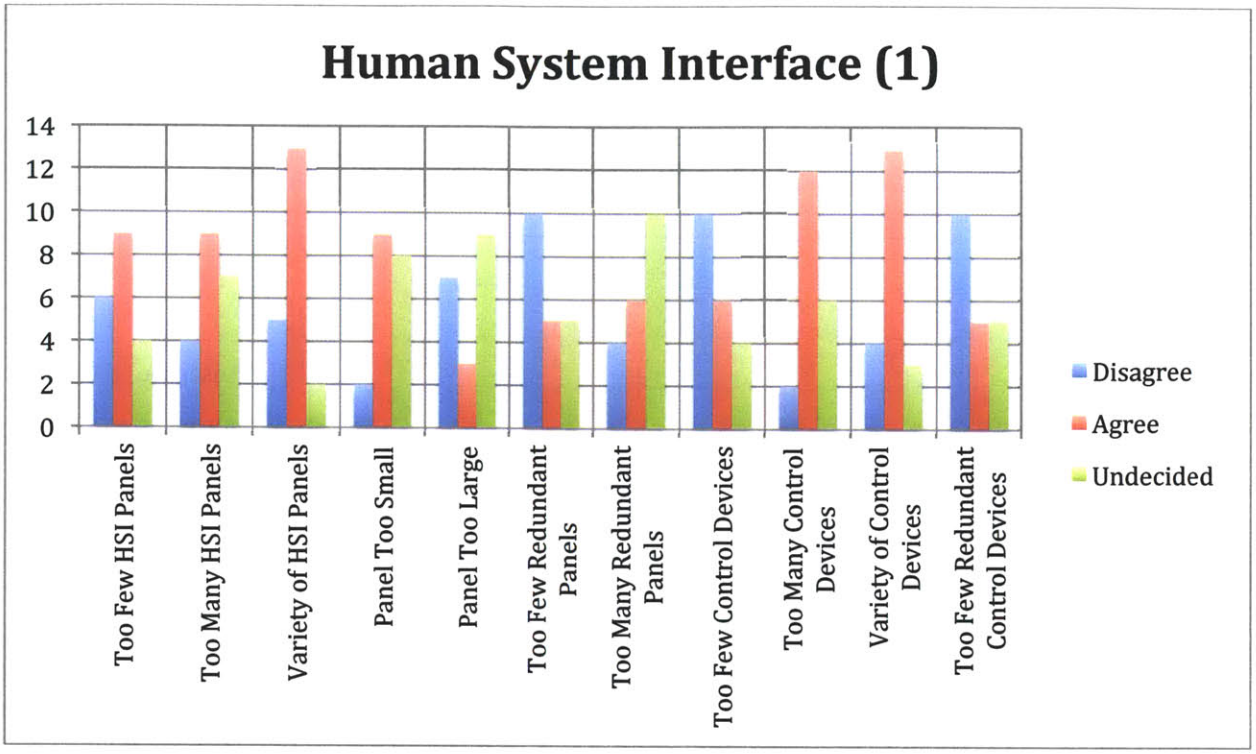


Figure 25. Ratings for human system interface factors (part 1)

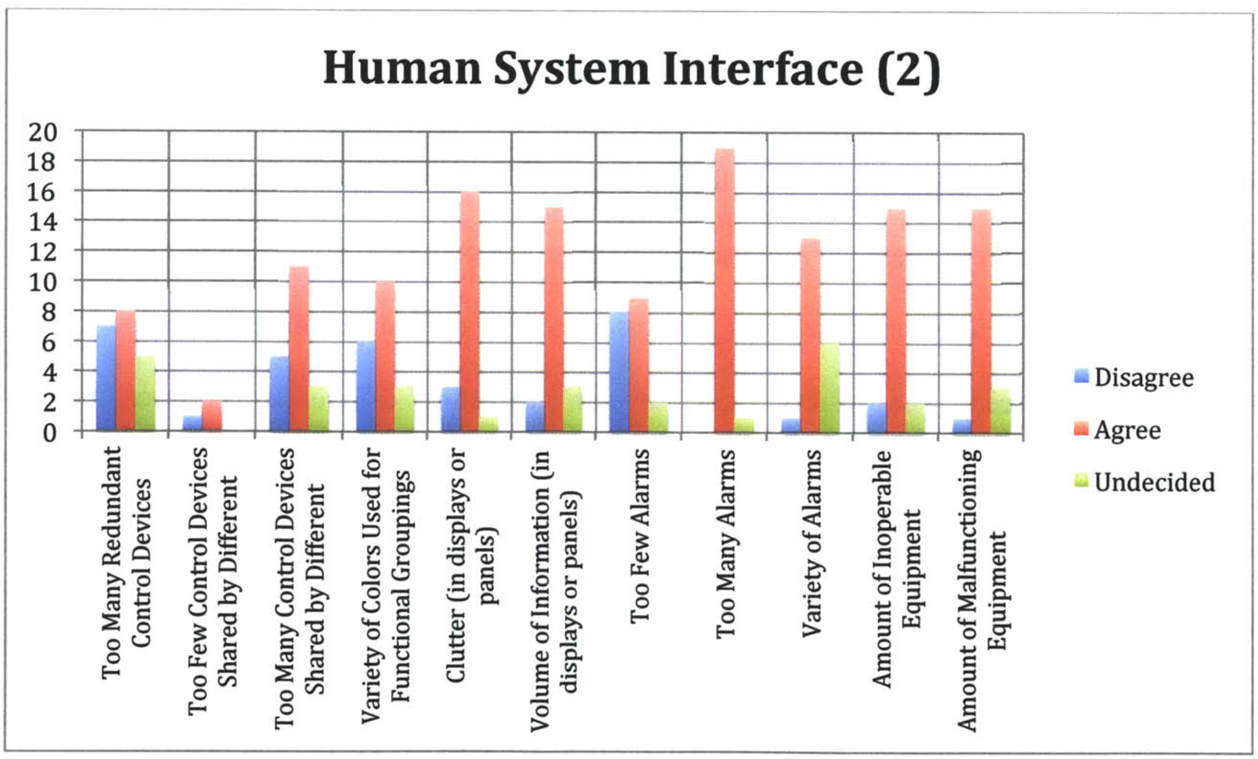


Figure 26. Ratings for human system interface factors (part 2)

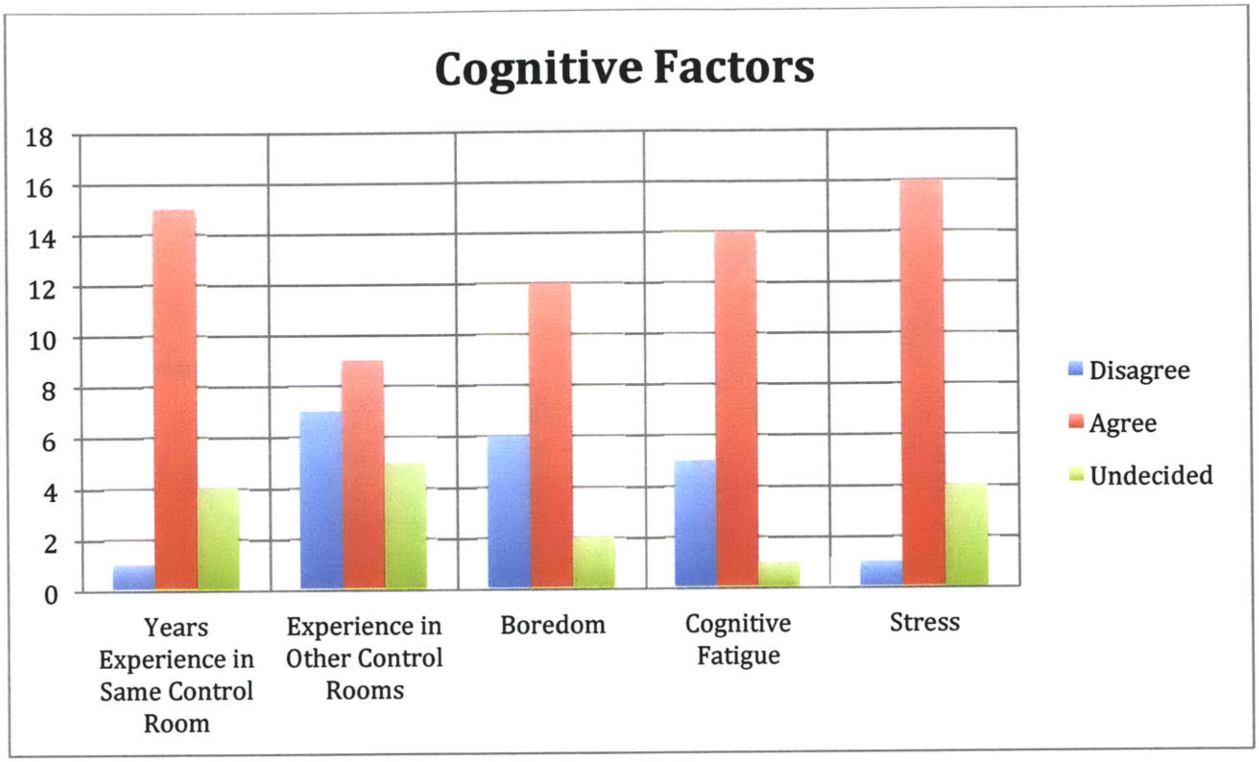


Figure 27. Ratings for cognitive factors

5.4.2 Stakeholder complexity view comparison

In order to address research question 3 ("Are there large variations between Designers, Operators and Reviewers views on complexity?"), the source ratings data collected from each group were used. The average rating for each source was then calculated for each stakeholder group and the averages were compared. The results show several interesting differences between the stakeholder group views on several sources, which support the hypothesis that different stakeholder groups think differently about complexity. Table 10 presents these differences. In general, the nature of most of these disagreements is not clear and need further investigation.

Table 10. Sources rating differences between the Reviewers, Designers and Operators

Source	Designers	Reviewers	Operators
Too many operational mode transitions	Agree	Disagree	Disagree
Frequency of operational mode transitions	Agree	Undecided	Disagree
Too few crew members available	Disagree	Disagree	Agree
Too many items on turnover sheet	Disagree	Undecided	Agree
Amount of required unit conversions	Agree	Agree	Disagree
Variety of procedures	Agree	Disagree	Undecided
Too many checkpoints	Agree	Disagree	Disagree
Too many steps in procedure	Agree	Disagree	Disagree
Too few crew members required to execute the task	Undecided	Disagree	Agree
Too few information sources to make an assessment	Agree	Agree	Disagree
Too many information sources to make an assessment	Agree	Disagree	Disagree
Level of assessment effort	Agree	Disagree	Undecided
Team unfamiliarity	Disagree	Agree	Agree
Shift length	Disagree	Agree	Agree
Inadequate simulator training	Disagree	Agree	Undecided
Experience in other control rooms	Disagree	Agree	Agree
Boredom	Agree	Disagree	Agree
Too few HSI panels	Agree	Disagree	Agree
Variety of HSI panels	Agree	Disagree	Agree
Too few control devices	Disagree	Agree	Agree
Too many redundant control devices	Agree	Disagree	Agree
Variety of control devices	Disagree	Agree	Disagree

5.4.2.1 Physical environment factors

Participants in the survey were generally in agreement about physical environment sources. As shown in Figure 28, all the stakeholder groups agreed with contribution of these sources to perceived complexity (i.e., the average ratings for sources were between three [neither agree of disagree] and five [strongly agree]). The only exception was "control room size" for which the Designers neither agreed nor disagreed.

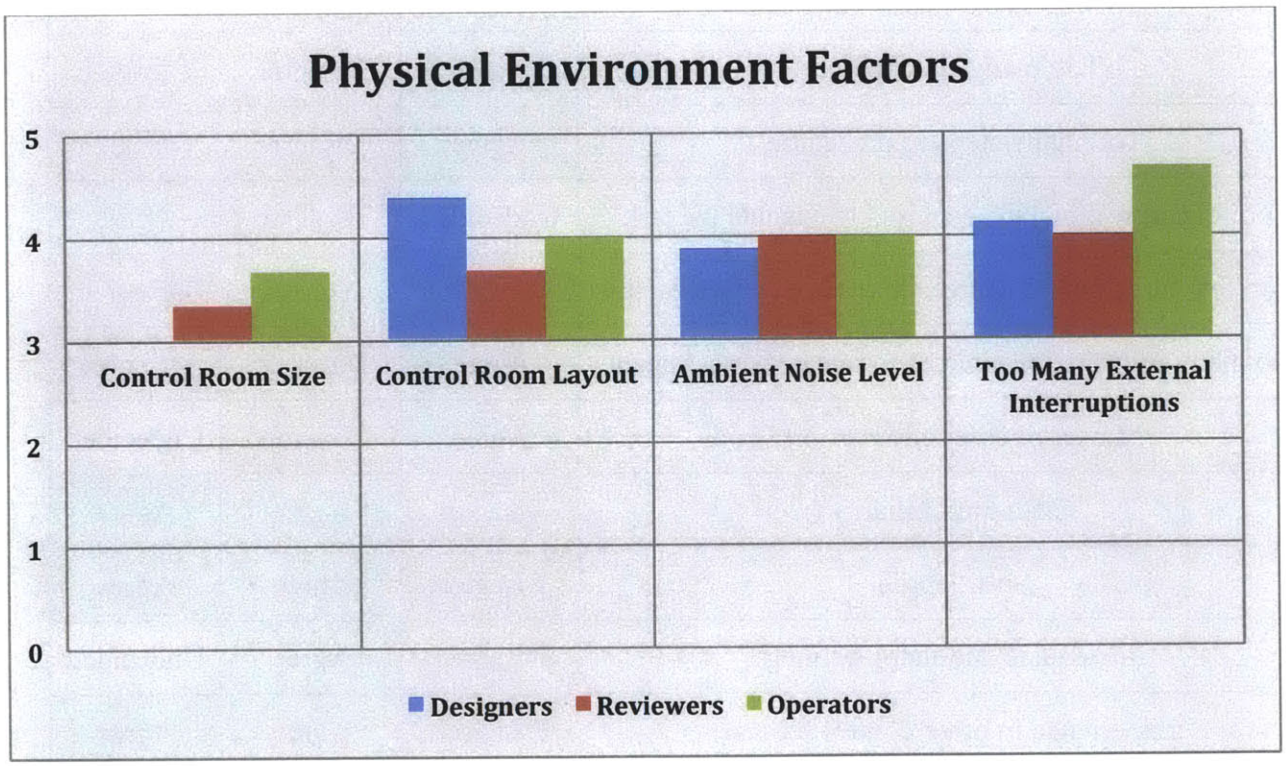


Figure 28. Differences in average ratings of different groups on physical environment factors

5.4.2.2 Task factors

As shown in Figure 29, the 3 groups of stakeholders were in disagreement for the majority of task factors (5 out of 7). An interesting result in this category was the difference in ratings for "Too few crew members available". Although Designers and Operators disagreed with the contribution of this source to perceived complexity, Operators highly agreed about this. On the other hand, all the 3 groups agreed on the contribution of "Too many crew members available". This result might reveal an important gap in operational knowledge of Designers and Reviewers with regards to team size.

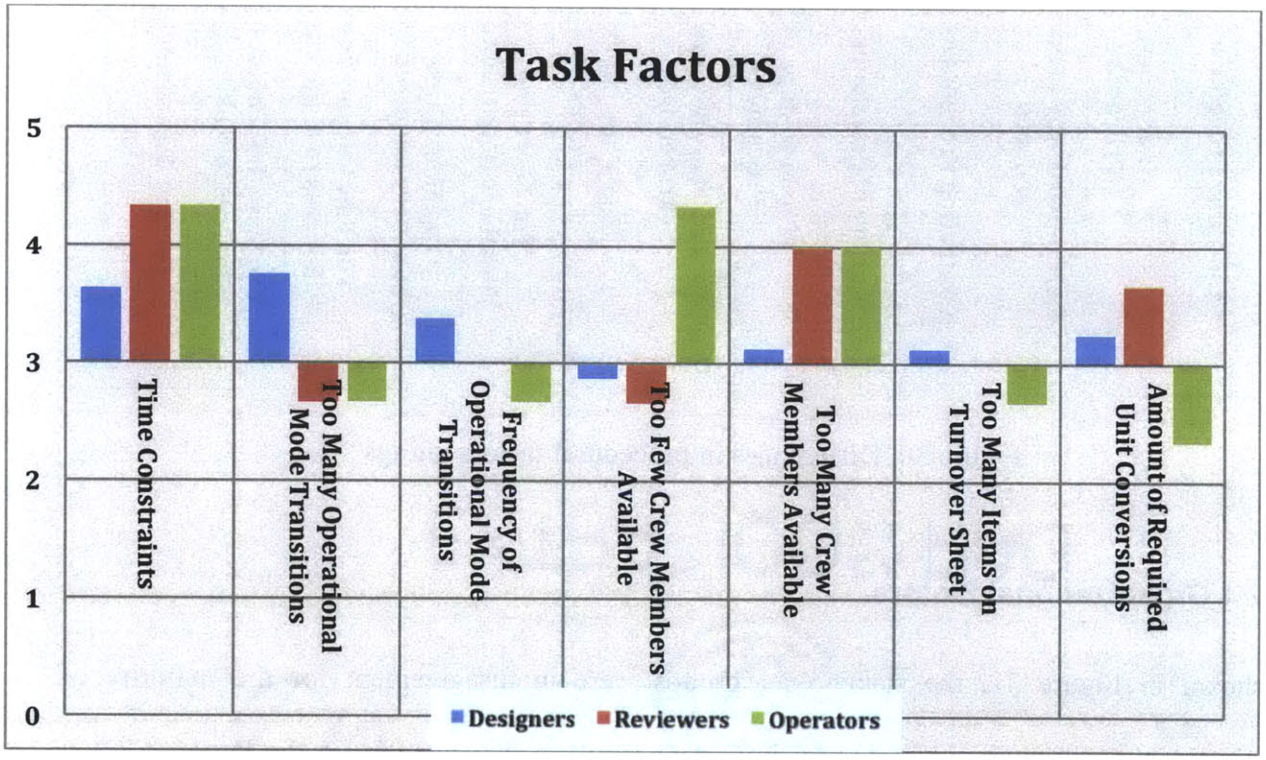


Figure 29. Differences in task factors ratings

5.4.2.3 Procedural factors

As shown in Figure 30, stakeholders were generally in disagreement with the majority of sources in this category (7 out of 13). In general, Designers agreed with the contribution of the majority of these sources to perceived complexity (11 out of 13). On the other hand, Reviewers disagreed with the majority of the procedural factors. This interesting gap between the views of Designers and Reviewers on procedural factors warrants more investigation.

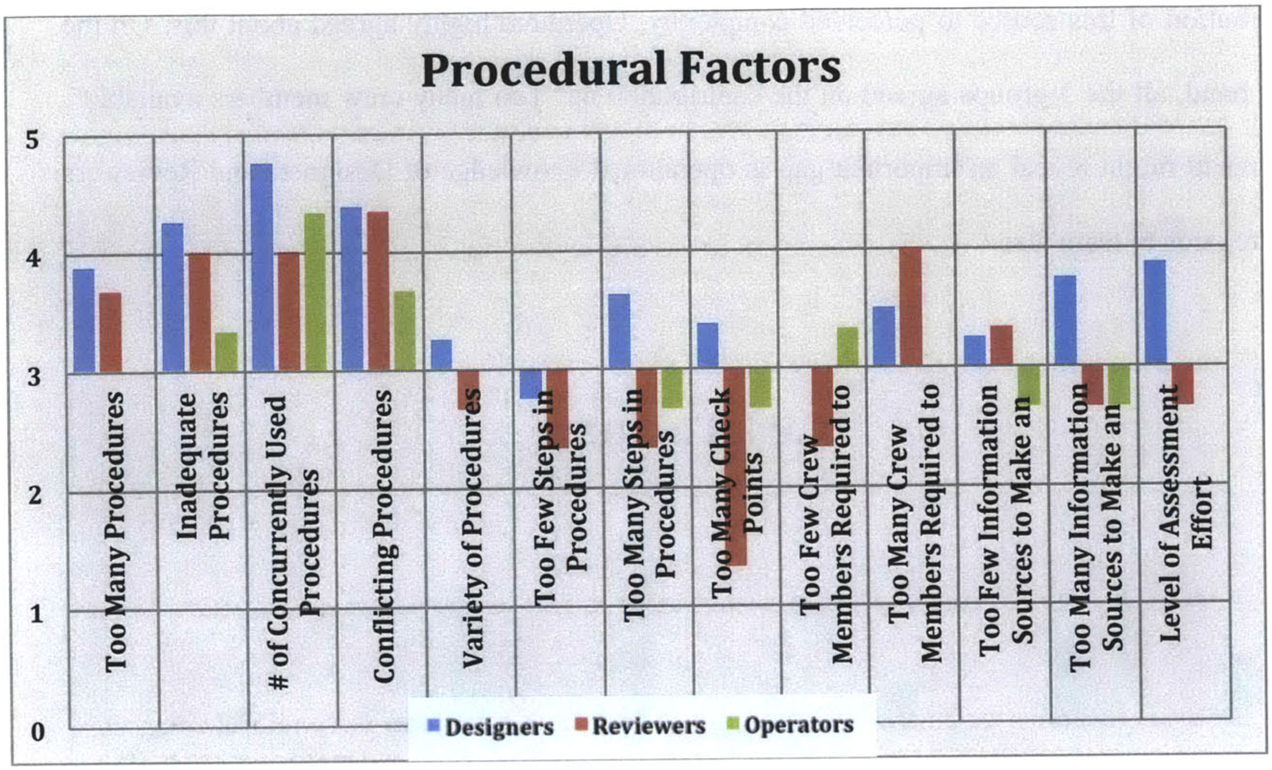


Figure 30. Differences in procedural factors ratings

5.4.2.4 Organizational factors

As shown in Figure 31, the stakeholder groups were in disagreement for the majority of organizational sources (3 out of 5). An important result in this category is the large variation between the Reviewers' view on training with Designers and Operators view. Although Reviewers strongly believe that inadequate or inaccurate training is an important issue that could affect perceived complexity, Designers and Operators disagreed or were undecided about or disagreed with this contribution. Some possible explanations for this large variation might be overconfidence in training.

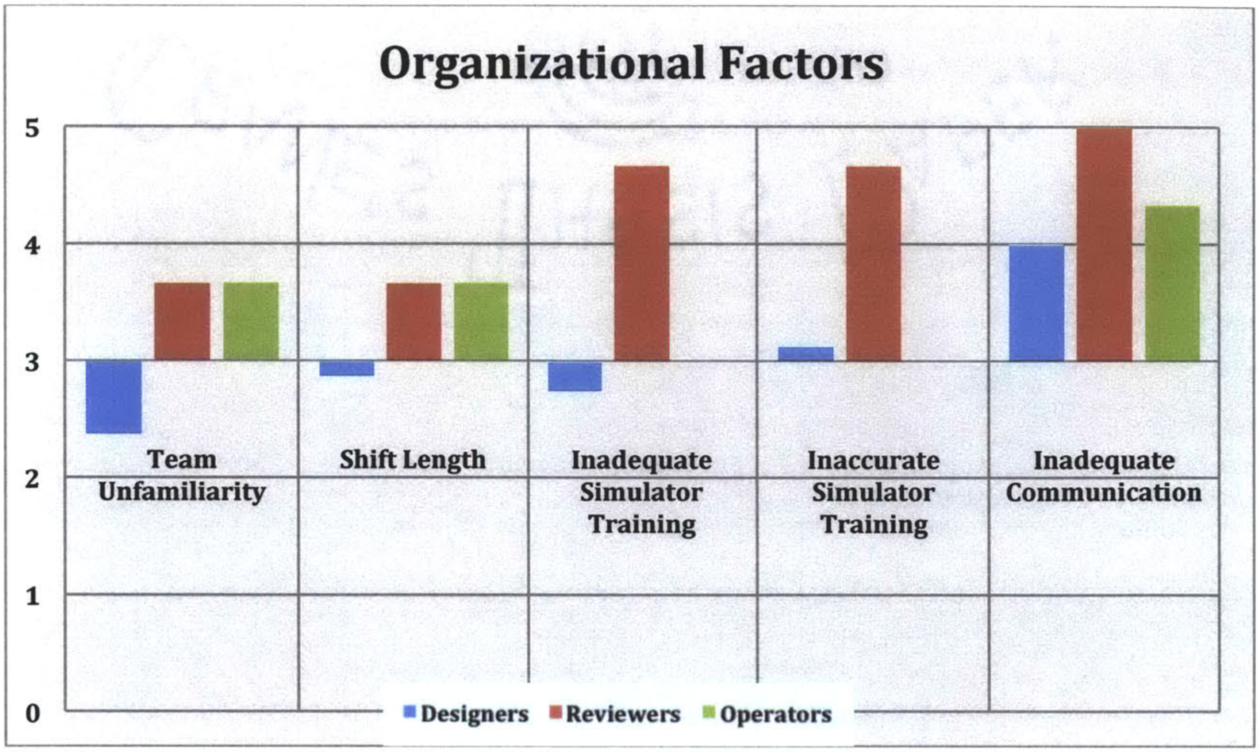


Figure 31. Differences in organizational factors ratings

5.4.2.5 Cognitive factors

Overall, the Designers, Reviewers and Operators were in agreement about the majority of cognitive sources (3 out of 5). As shown in Figure 32, the main source of disagreement between the stakeholders is "boredom". Although Reviewers disagreed with the contribution of boredom to perceived complexity, Operators strongly believed that boredom is an important factor contributing to their perceived complexity. On the other hand, the 3 groups agreed on the role of "cognitive fatigue" in perceived complexity. Since boredom and fatigue are two ends of the spectrum when it comes to workload, stakeholders' agreement on the effects of high workload on perceived complexity and their disagreement on the effects of low workload warrants further investigation.

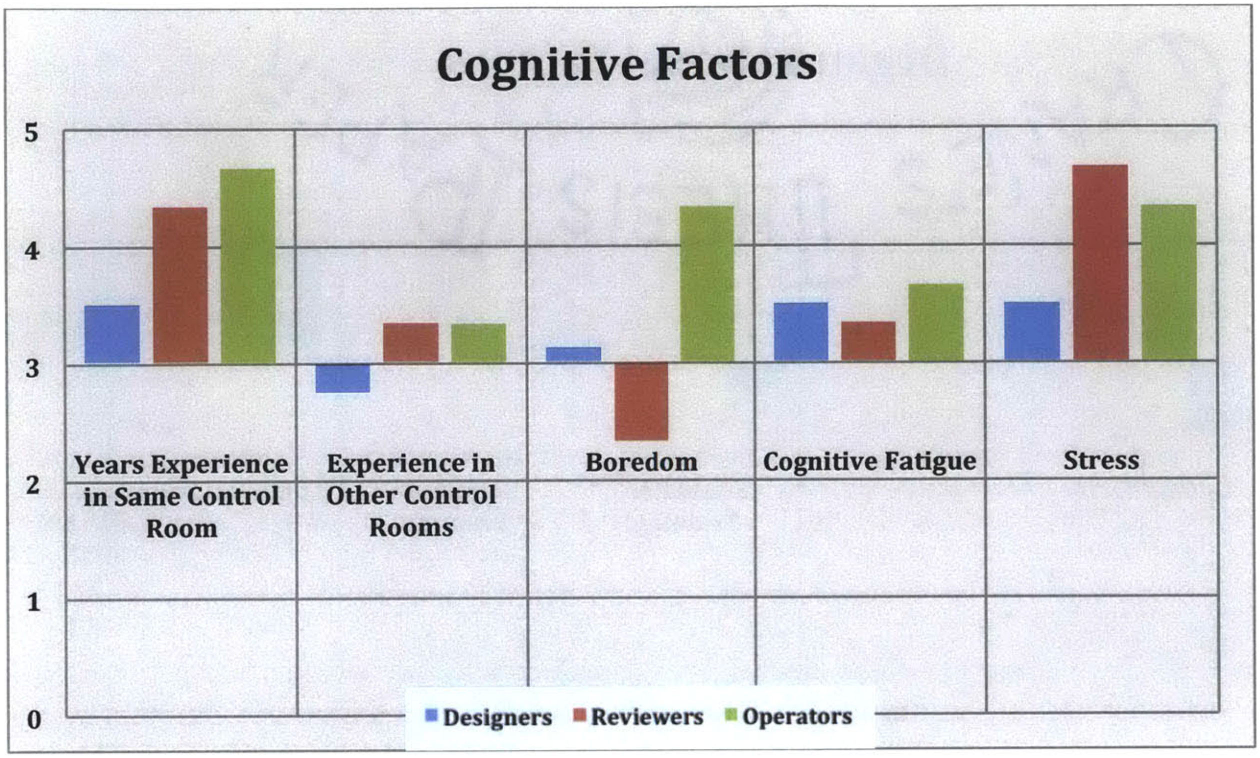


Figure 32. Differences in cognitive factors ratings

5.4.2.6 Human system interface factors

The result of the survey shows a high degree of agreement between the stakeholder groups on the majority of human system interface factors (17 out of 22). Reviewers were the group who disagreed the most with the sources in this category (10 out of 22 sources).

In conclusion, a list of important complexity sources was presented that could be used as the initial step in future complexity mitigation approaches. Overall, the results discussed in this chapter provide some evidence for a large variation between the complexity view of Designers and the objective evidence gathered from the incident report databases (i.e., a large Δ in Figure 2). In addition, as hypothesized in Chapter 3, these results show gaps between the mental models of Designers, Operators and Reviewers with regards to sources that contribute to perceived complexity (i.e., δs in Figure 2). In particular, the stakeholders were in agreement on the majority of sources related to physical environment, human system interface, and cognitive complexity with the exception of "boredom". Although Operators admitted that boredom had a strong contribution to their perceived complexity, and hence the overall performance, Reviewers and Designers were reluctant to admit or were unaware of the importance of the implications of boredom in the NPP operations. This finding points to an important organizational problem that warrants further investigation. Moreover, extreme disagreement in views about organizational factors, task factors and procedural factors needs further examination.

6. CONCLUSION AND FUTURE WORK

In this research, a methodology to study perceived complexity in NPP control rooms is proposed. The method investigates the sources that make a control room complex to the eyes of the human operators using a systems approach. Next generation NPP control rooms may challenge human cognitive limitations by presenting information in complex ways. In order to mitigate important complexity sources that contribute to human performance, it is vital not only to identify such sources, but also the disparities between the objective evidence and the subjective complexity views of the stakeholders to ensure that complexity considerations in the NPP control room designs and approval of such designs are realistic (considering the available evidence). Systematic analyses of previous incidents, an extensive literature review and operator interviews led to the generation of some of the potential sources of complexity that may contribute to human performance. Network representation (complexity source network) was used to identify the interconnections between such sources. Measuring complexity in a network was proposed as analogous to measuring the number of nodes/links and their interconnections. Therefore, mitigating complexity of such networks could be achieved by reducing its connectivity. In order to facilitate this investigation and analysis, a network information visualization and analysis called CXViz was implemented. CXViz not only enables a visual analysis of the most important contributors in complexity networks, but also provides several important connectivity measures of such networks.

In order to investigate the hypothesis that network representations can effectively represent NPP system complexity and provide a roadmap for complexity mitigation, networks need to be constructed from both objective and subjective complexity data for further analysis. It is important to understand how subjective stakeholder views of complexity differ from an objective complexity perspective in order to understand gaps in the mental models between operators, designers, and regulatory entities. It was proposed that objective complexity can be measured for NPP systems via NRC-approved databases, however such measurements are actually only quasi-objective since the databases also represent human consensus.

An evidence-based approach was used to identify objective evidence to support the identified sources. 22 previous incidents included in the HERA database were parsed and an evidence database was created. Using the available evidence the ranking of the most common or most supported sources (across the 22 incidents) and the most connected sources in the aggregate CSN was reported. The results showed a strong homogeneity between the two rankings. In addition, it was found that the top 5 sources in the most supported ranking account for the majority of the available evidence. "Stress", "Available Time", and "Inadequate Procedures" were the three sources that were included in the top 5 for both rankings. This result provides the first and necessary step in targeting specific sources for mitigation design within the nuclear power plant control room.

In order to facilitate the subjective data collection and analysis, a dynamic survey called CXSurvey was developed. Three groups of stakeholders, Designers, Reviewers and Operators were chosen and a survey-interview method was used to collect subjective complexity data from representatives of each group. Interviewees were asked to rate the identified sources in terms of contribution to perceived complexity, rank the top 5, and to identify some of the links between the sources in a customized CSN (based on their ratings and ranking of sources). The top 5 rankings from each stakeholder group were compared to the objective top 5 sources (from the most supported ranking) to identify potential gaps between the mental models of different groups and the objective reality of the previous incidents under investigation.

The results showed large variations between the complexity view of Designers and Operators with the objective complexity evidence. Designers in particular did not acknowledge any of the top 5 most supported (objective) sources. On the other hand, Reviewers were more in line with the objective evidence from the previous incidents. These results show: 1) There's a significant disparity between what designers and operators think the sources of complexity are and the objective reality of the past incidents investigated in this research. Due to low probability of incidents in the NPP domain, any evidence for recurrent problems should be investigated thoroughly and be considered in the new designs. Therefore, the fact that designers did not acknowledge many of these recurrent problematic sources could indicate a problem. 2) According to the results, the need for the addition of complexity considerations in the human factors design review guidelines is warranted. 3) Since the reviewers' views on complexity were close to the objective evidence obtained in this research, a more effective communication mechanism between the NRC and control room designers or operators might help aligning their views on complexity. Finally, 4) these results might indicate the lack of a systematic incident analysis mechanism to learn collectively from the past incidents. In particular, these results show that such systematic learning may not be reflected in the operator training modules.

Finally, the analysis of source ratings showed large variations between the way Designers, Reviewers and Operators think about sources of complexity. Overall, the 3 groups were in disagreement on a majority of task factors, procedural factors and organizational factors. In addition, although the 3 groups were in agreement on the majority of cognitive factors, their views on the role of boredom as a source of perceived complexity differs significantly. Although Operators admit the importance of boredom in their perceived complexity, NRC Reviewers disagreed with the contribution of boredom to perceived complexity. This result warrants further investigation since previous research provides evidence for the negative effects of boredom on operator performance in human supervisory control domains (Kass, Vodanovich, Stanny, & Taylor, 2001; Thackray, Powell, Bailey, & Touchstone, 1975). These findings warrant further investigation of these important intra-organizational problems.

6.1 Future Work

In this section, several important directions for future work are discussed. First, the rankings of important sources discussed in Chapter 6 could be utilized to mitigate the effects of perceived complexity on operator performance and overall plant safety. The identified sources could be prioritized in terms of likelihood of mitigation or difficulty of mitigation due to technical or other factors. Nodes could be removed from the complexity source networks and the effects of removing nodes on the overall complexity of the network could be analyzed. In addition controlled experiment could be used to investigate the effects of mitigating a source (nodes) or an interaction (links).

Due to several limitations in accessing data, both in terms of number of incidents reported and the access to stakeholders, iterations are an important aspect of the proposed methodology. New incidents could be added to the HERA database or analyzed from similar incident report databases to improve the validity of the results, refine the list of sources and improve the evidence database. Additional coders could repeat content analysis of the HERA to improve the inter-coder reliability and to refine the available evidence. Furthermore, to improve the validity of the result, additional interviewees from each stakeholder group should be identified and interviewed.

Complexity source networks could be analyzed further to provide more insight about the incidents. First, the emergence of a CSN over time could be analyzed to shed some light on the nature of interactive complexity between the sources. Next, CSNs for different incidents could be compared to identify common patterns of interactions between the nodes and different complexity levels.

Lastly, important gaps between the subjective complexity view of the stakeholders and the objective complexity evidence should be further investigated. Further data collection including structured stakeholder interview or focus groups is needed to understand the causes of such gaps and to provide insight into potential mitigating actions. In addition, important gaps between the complexity views of the stakeholder groups should be further investigated. Additional data collection may help identifying the reasons for such differences and potential alignment policies could be developed accordingly.

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Appendix A: Complexity Questionnaire

Questionnaire for Managing Complexity in Nuclear Power Plant Control Rooms

Thanks for participating in this interview. Your input is extremely valuable and will be considered in the design of new generation control rooms.

Instructions: This questionnaire asks you to answer to a series of questions regarding the Nuclear Power Plant (NPP) control room you have worked in. Part I asks for some demographic information about your job. For Part II questions, please read the questions (in bold) carefully, then while thinking about the question, circle the number that best fits your opinion for each numbered argument. If you have any comments about the general question, please provide them in the space available. For Part III, please answer on the provided sheet. Please answer each question to the best of your ability.

*Please remember that the information you provide is confidential and is only being used for educational purposes. You don't need to provide any identifiable information about yourself.

**For the purposes of this questionnaire we define "display" as all the digital displays including computer monitors.

Part I

What is the name of the NPP you are operating in (or most recently operated in)?

What is the type of NPP you are operating in (or most recently operated in)? (e.g. Research, Commercial, Military)

How long have you been licensed?

How many years have you worked in this particular control room?

How many years have you worked as an NPP operator in total?

If you are no longer working as an operator, how long has it been since you were an ac- tive operator?

How many control rooms have you been worked in? If more than one, please list the names and types of NPPs.

Part II

Please circle the number corresponding to your agreement to the particular statement.

	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
1. Does the variety of display features assist you in acquiring information?					
1.1. The following visual features assist me in acquiring the information in the control room:					
1.1.1. Variety of **colors** in the displays assists me in acquiring information.	5	4	3	2	1
1.1.2. Variety of **shapes** in the displays assists me in acquiring information.	5	4	3	2	1
1.1.3. Variety of **font sizes** in the displays assists me in acquiring information.	5	4	3	2	1
1.1.4. Variety of **icons** in the displays assists me in acquiring information.	5	4	3	2	1
1.1.5. Variety of **graphics** in the displays assists me in acquiring information.	5	4	3	2	1
1.2. The following auditory features assists me in assessing the situation in the control room:					
1.2.1. Variety of **audio alarms** assist me in assessing the situation.	5	4	3	2	1
1.2.2. The **audio alarms** can be distracting.	5	4	3	2	1
1.3. The displays use too many different:					
1.3.1. Colors	5	4	3	2	1
1.3.2. Fonts	5	4	3	2	1
1.3.3. Shapes	5	4	3	2	1
1.3.4. Icons	5	4	3	2	1
1.3.5. Auditory alarms	5	4	3	2	1
1.3.6. Windows	5	4	3	2	1
1.4. I obtain information better if I ignore some details like:					
1.4.1. Colors	5	4	3	2	1
1.4.2. Fonts	5	4	3	2	1
1.4.3. Text formats	5	4	3	2	1
1.4.4. Graphics	5	4	3	2	1
1.4.5. Alarms	5	4	3	2	1

Note:	

2. How does the variety of control devices (e.g. buttons, knobs, etc.) assist you in control operations?	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
2.1. The variety of control device **sizes** assists me in control operations.	5	4	3	2	1
2.2. The variety of control device **colors** assists me in control operations.	5	4	3	2	1
2.3. The variety of control device **shapes** assists me in control operations.	5	4	3	2	1
2.4. The variety of control device **text/descriptions** assists me in control operations.	5	4	3	2	1
2.5. The physical layout of the control devices assists me in locating them.	5	4	3	2	1
2.6. The physical layout of the control devices assists me in using them.	5	4	3	2	1
2.7. The control devices use too many different:					
2.7.1. hardware controls like dials/levers/buttons	5	4	3	2	1
2.7.2. soft, programmed buttons	5	4	3	2	1
2.7.3. sizes	5	4	3	2	1
2.7.4. colors	5	4	3	2	1
2.7.5. fonts	5	4	3	2	1
2.7.6. shapes	5	4	3	2	1
2.7.7. icons	5	4	3	2	1
2.8. I can see the controls better if I ignore some of the details such as:					
2.8.1. Colors	5	4	3	2	1
2.8.2. Layout	5	4	3	2	1

2.8.3. Text format	5	4	3	2	1
Note:					
3. How would you evaluate the overall complexity of the control room?	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
3.1. The control room is too busy from a visual perspective.	5	4	3	2	1
3.2. Displays are easily distinguishable at first glance.	5	4	3	2	1

3.3. Control devices are easily distinguishable at first glance.	5	4	3	2	1
3.4. The displays are readable from my control station.	5	4	3	2	1
3.5. I have to stare at the displays for a while to read the information.	5	4	3	2	1
3.6. Adequate space between different displays exists.	5	4	3	2	1
3.7. Adequate space between different control devices exists.	5	4	3	2	1
3.8. I have difficulty remembering what different alarms mean.	5	4	3	2	1
3.9. I can effectively acquire information.	5	4	3	2	1
3.10. The control room layout is simple and easy to work in.	5	4	3	2	1
3.11. It is sometimes difficult to find all the information I need.	5	4	3	2	1
3.12. I do not like the control room layout because it is too complex.	5	4	3	2	1
3.13. I can effortlessly understand the information presented in the control room.	5	4	3	2	1
3.14. Working in this control room takes a significant amount of mental effort.	5	4	3	2	1
3.15. I feel overwhelmed by the amount of information presented.	5	4	3	2	1
3.16. More displays are needed in the control room.	5	4	3	2	1
Note:					

4. How would you evaluate the overall complexity of the displayed information in the control room?	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
4.1. I can easily identify an alarm in a timely manner.	5	4	3	2	1
4.2. I have difficulty recognizing the situation when an alarm sounds.	5	4	3	2	1
Note:					

5. Some of the information presented in the control room is frequently updated. How do information changes on the displays affect the way you process information?	Strongly Agree / Agree / Undecided / Disagree / Strongly Disagree

	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
5.1. Most information changes are predictable.	5	4	3	2	1
5.2. Most information changes are easy to track.	5	4	3	2	1
5.3. Keeping track of information changes distracts me from performing my primary tasks (makes me too busy).	5	4	3	2	1
5.4. The displayed information should change less frequently.	5	4	3	2	1

Note:

6. How do the physical interactions within the control room affect you?	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
6.1. The interaction with the control devices requires too many actions to perform tasks.	5	4	3	2	1
6.2. The amount of interaction required to perform tasks does not bother me.	5	4	3	2	1
6.3. The interactions required to accomplish my tasks can confuse me.	5	4	3	2	1
6.4. I feel overwhelmed by the amount of interaction required by the system.	5	4	3	2	1
6.5. I have to manage more than one action sequence to get a task done.	5	4	3	2	1
6.6. I can perform most tasks by following a single action sequence.	5	4	3	2	1
6.7. I might forget the actions needed to complete a task when I am busy.	5	4	3	2	1
Note:					

7. How does going through procedure steps affect your performance?	Strongly Agree	Agree	Undecided	Disagree	Strongly Disagree
7.1. I have to access too many displays to perform a specific task.	5	4	3	2	1
7.2. I can effortlessly follow procedures to acquire information.	5	4	3	2	1
7.3. I can effortlessly follow procedures to perform tasks.	5	4	3	2	1
7.4. I have trouble performing tasks because there are so many steps in the procedure.	5	4	3	2	1
7.5. I have difficulty keeping track of constant action items in the procedure.	5	4	3	2	1
7.6. I use workarounds (post-it notes, etc.) to remember more than one procedure step at a time.	5	4	3	2	1
7.7. The environment around me (e.g. alarms) adds to my stress level.	5	4	3	2	1

Note:	

Part III

1. How long is your shift? What do you typically do during this time?

2. What percentage of your shift do you consider as low workload? Have you ever felt bored during your shift?

3. What percentage of your job involves monitoring digital displays? How many do you typically monitor? Is this more or less than what you need?

4. Can you imagine a situation where an operator could feel overloaded by the information available to him/her on the displays? Please explain.

5. Can you imagine a situation where an operator would want more information available to him/her on the displays? Please explain.

6. Can you name some of the mistakes that could happen in your work environment (e.g. near miss, major incident, minor incident, easily forgotten mistake)? What are the causes of these mistakes?

7. In an alarm situation, how would you rate (easy to difficult) transitioning from steady state monitoring to an emergency procedure? How long does it take to find the necessary information to execute a procedure?

8. How often do you encounter alarms? How long does it take to understand the situation?

9. What is the most important information you look at? Why is it the most important?

10. How complex is your job? What makes it complex or not?

11. What is the most complex display you look at/interact with? What makes it the most complex?

12. How would you change the following list of major responsibilities of a nuclear power plant operator? (Add, combine, subtract)

    Responsibilities:

    - Reactivity control
    - Maintain reactor core cooling
    - Maintain reactor coolant system integrity
    - Maintain containment integrity
    - Control of radioactive effluents
    - Start-up control
    - Steam generation
    - Electricity generation
    - Shutdown & Refueling control
    - Fuel Management

Do you have any other comments or suggestions?

Appendix B: List of Sources of Complexity

1. Initial List of Sources of Complexity

Environmental Complexity
1. Control room size 2. Control room layout 3. Operational mode duration 4. Frequency of operational mode transitions 5. Number of operational mode transitions 6. Number of critical events in the last shift 7. Number of external interruptions 8. Ambient noise level

Organizational Complexity
1. Number of procedures 2. Variety of procedures 3. Number of dependent procedures 4. Number of parallel procedures 5. Number of collaborative procedure 6. Number of procedure switches 7. Duration between procedures 8. Duration of procedures 9. Number of required inferences per procedure 10. Number of steps in procedures 11. Number of information sources per inference 12. Number of crew members 13. Number of crew members required for each procedure 14. Number of team hierarchy levels 15. Shift length

Interface Complexity
16. Number of displays 17. Variety of displays 18. Display size 19. Display resolution 20. Display luminance 21. Number of animated display features 22. Number of shared displays 23. Number of redundant displays 24. Distance between displays 25. Number of control devices 26. Variety of control devices 27. Number of shared control devices 28. Number of redundant control devices 29. Distance between control devices 30. Distance between control devices and displays 31. Distance between controls and their associated displays 32. Clutter 33. Information amount 34. Number of alarms 35. Variety of alarms 36. Alarm duration 37. Variety of icons 38. Icon Size 39. Variety of fonts 40. Font size 41. Variety of colors 42. Text to graphics ratio 43. Refresh rate 44. Real-time update rate 45. Number of required unit conversions

Cognitive Complexity
46. Number of years of experience in different control rooms 47. Number of years of experience in same control room 48. Number of years working with the same crew (team unfamiliarity) 49. Number of simulator hours completed per operator 50. Boredom 51. Cognitive Fatigue

2. Sources of Complexity Used in CXViz (*sources that were added after the HERA content analysis are shown in red*)

Environmental Complexity
1. Control room size 2. Control room layout 3. *Available time* 4. Operational mode duration 5. Frequency of operational mode transitions 6. Number of operational mode transitions 7. Number of critical events in the last shift 8. Number of external interruptions 9. Ambient noise level

Organizational Complexity
10. Number of procedures 11. Variety of procedures 12. Number of dependent procedures 13. Number of parallel procedures 14. Number of collaborative procedure *15. Conflicting procedures* *16. Inadequate procedures* 17. Number of procedure switches 18. Duration between procedures 19. Duration of procedures 20. Number of required inferences per procedure 21. Number of steps in procedures *22. Number of inferences per step* *23. Number of information sources per step* *24. Duration between steps* *25. Duration of steps* 26. Number of information sources per inference *27. Number of required unit conversions* *28. Variety of required unit conversions* 29. Number of crew members 30. Number of crew members required for each procedure 31. Number of team hierarchy levels 32. Shift length *33. Incorrect simulations* *34. Inadequate communication*

Interface Complexity
35. Number of displays 36. Variety of displays 37. Display size 38. Display resolution 39. Display luminance 40. Number of animated display features 41. Number of shared displays 42. Number of redundant displays 43. Distance between displays 44. Number of control devices 45. Variety of control devices 46. Number of shared control devices 47. Number of redundant control devices *48. Number of inoperable modules* *49. Number of malfunctioning module* 50. Distance between control devices 51. Distance between control devices and displays 52. Distance between controls and their associated displays 53. Clutter 54. Information amount 55. Number of alarms 56. Variety of alarms 57. Alarm duration 58. Variety of icons 59. Icon Size 60. Variety of fonts 61. Font size 62. Variety of colors *63. Number of visualizations* 64. Text to graphics ratio 65. Refresh rate 66. Real-time update rate

Cognitive Complexity
67. Number of years of experience in different control rooms 68. Number of years of experience in same control room 69. Number of years working with the same crew (team unfamiliarity) 70. Number of simulator hours completed per operator 71. Boredom 72. Fatigue

3. Sources of Complexity and Definitions Used in CXSurvey

1. Control Room Size:
   The size of the control room.

2. Control Room Layout:
   The layout of the modules and devices in the control room.

3. Ambient Noise Level:
   The amount of background noise in the control room.

4. Too Many External Interruptions:
   There are too many external interruptions during control room operations.

5. Time Constraints:
   There is too little time to accomplish the necessary tasks.

6. Too Few Operational Mode Transitions:
   There are not enough switches between operational modes (e.g. normal, off-normal and emergency) during a shift.

7. Too Many Operational Mode Transitions:
   There are too many switches between operational modes (e.g. normal, off-normal and emergency) during a shift.

8. Frequency of Operational Mode Transitions:
   There is a need to switch back and forth between operational modes (e.g. normal, off-normal, and emergency) very quickly or slowly.

9. Too Few Crew Members Available:
   There are not enough crewmembers available to accomplish the necessary tasks.

10. Too Many Crew Members Available:
    There are too many crewmembers around to accomplish the necessary tasks.

11. Too Few Items on Turnover Sheet:
    There are not enough items on each turnover sheet.

12. Too Many Items on Turnover Sheet:
    There are too many items on each turnover sheet.

13. Amount of Required Unit Conversions:
    The number of unit conversions required completing a task.

14. Too Few Procedures:
    There are not enough procedures in the control room.

15. Too Many Procedures:
    There are too many procedures in the control room.

16. Inadequate Procedures:
    The procedures available in the control room are insufficient in some situations.

17. Too Few Concurrently Used Procedures:
    There are not enough procedures that can be used at the same time.

18. Too Many Concurrently Used Procedures:
    There is a need to follow many procedures simultaneously.

19. Conflicting Procedures:
    Some procedures in the control room give instructions that conflict with each other.

20. Variety of Procedures:
    There are many different types of procedures available in the control room.

21. Too Few Steps in Procedures:
    There are not enough steps in each control room procedure.

22. Too Many Steps in Procedures:
    There are too many steps in each control room procedure.

23. Amount of Check Points:
    The amount of "if then" statements in a procedure.

24. Too Few Crew Members Required to Execute Procedure:
    The number of crewmembers called for to execute a procedure is insufficient.

25. Too Many Crew Members Required to Execute Procedure:
    There are too many crewmembers called for to execute a procedure.

26. Too Few Information Sources to Make an Assessment:
    There are not enough information sources available (e.g. panels, charts, teammates) to make a necessary assessment.

27. Too Many Information Sources to Make an Assessment:
    There are too many information sources present (e.g. panels, charts, teammates) to make an accurate assessment.

28. Level of Assessment Effort:
    Level of difficulty to integrate and analyze information from multiple sources.

29. Team Unfamiliarity:
    The crewmembers have not spent much time working with the other crewmembers on their team.

30. Shift Length:
    The length of each work shift in the control room.

31. Inadequate Simulator Training:
    Not enough simulator training.

32. Inaccurate Simulator Training:
    There are inconsistencies between the simulation environment and the real plant.

33. Inadequate Communication:
    There is not enough communication between crewmembers and the communication that exists is not sufficient to perform all the necessary tasks.

34. Too Few HSI Panels:
    There are not enough HSI panels in the control room.

35. Too Many HSI Panels:
    There are too many HSI panels in the control room.

36. Variety of HSI Panels:
    There are a number of different types of HSI panels in the control room.

37. Panel Too Small:
    The panels in the control room are too small.

38. Panel Too Large:
    The panels in the control room are too large.

39. Too Few Redundant Panels:
There are not enough of the same panels spread about the control room.

40. Too Many Redundant Panels:
The same panels appear too many times in the control room.

41. Too Few Control Devices:
There are not enough control devices in the control room.

42. Too Many Control Devices:
There are too many control devices in the control room.

43. Variety of Control Devices:
There are many different types of control devices in the control room.

44. Too Few Redundant Control Devices:
There are not enough of the same modules or control devices in the control room.

45. Too Many Redundant Control Devices:
There are too many of the same modules or control devices in the control room.

46. Too Few Control Devices Shared by Different Systems:
There are not enough of the same control devices used to control multiple systems/modules.

47. Too Many Control Devices Shared by Different Systems:
There are too many of the same control devices used to control multiple systems/modules.

48. Variety of Colors Used for Functional Groupings:
The number of different types of colors used for functional groupings in the control room.

49. Clutter (in displays or panels):
Presenting an excessive amount of information in a display or panel.

50. Volume of Information (in displays or panels):
The amount of information presented to the operator at any time using different panels/displays.

51. Too Few Alarms:
There are not enough alarms in the control room.

52. Too Many Alarms:
    There are too many alarms in the control room.

53. Variety of Alarms:
    There are many different types of alarms in the control room.

54. Amount of Inoperable Equipment:
    Amount of equipment that is not in a safe and reliable functioning condition.

55. Amount of Malfunctioning Equipment:
    Amount of equipment that is functioning incorrectly.

56. Years Experience in Same Control Room:
    The number of years spent working in the same control room.

57. Experience in Other Control Rooms:
    Too much experience in other control room(s) may confuse the operator.

58. Boredom:
    The long durations of inactivity may increase the perceived complexity of the control room.

59. Cognitive Fatigue:
    Night shifts and long shifts may increase the perceived complexity of the control room.

60. Stress:
    The amount of stress perceived by control room staff may increase the perceived complexity of the control room.

Appendix C: HERA Database Analysis

As discussed in Chapter 4 each incident in HERA is organized by hundreds of sub-events. Particular actions were coded according to conventional probabilistic risk assessment (PRA) methods (Halbert et al., 2006). Each of the 22 events in the HERA database was examined for the performance-shaping factor (PSF) class of complexity. Each of the PSFs that were coded as a human error (XHE) or human success (HS) due to complexity were examined and recorded.

Event	Indian Point 2 2/15/2000		Browns Ferry 1		Salem 1		North Anna 1		Crystal River 3		Calvert Cliffs 1	
Human Errors (XHEs) & Human Successes (HSs) Performance-Shaping Factors in Complexity	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS
Causal connections apparent (positive)	1			1								3
Simultaneous tasks with high attention demands	5	1			10	1	3	1	2			
Extensive knowledge regarding the physical layout of the plant is required	1	1		1							1	
Coordination required between multiple people in multiple locations		1										
Demands to track and memorize information	1				2							
Ambiguous or misleading information present	1								3	1		
Information fails to point directly to the problem	1	2			4		1		3			
System dependencies are not well defined	1										5	
Scenario demands that the operator combine information from different parts of the process and information systems				3	2						3	6
Loss of plant functionality complicates recovery path				4								
Presence of multiple faults				1								
Problems in differentiating important from less important information					1		2				5	
Other						1						
Worker distracted/ interrupted					1		1					
High number of alarms							1	1				
Weak causal connections exist											1	
General ambiguity of the event									3			3
Dependencies well defined (pos)												
Few or no concurrent tasks (pos)												
Difficulties in obtaining feedback												
Complexity Sums	11	5	0	10	20	2	8	2	11	1	15	12

Event	Waterford 3		La Salle 2		Quad Cities 2		Davis-Besse		Point Beach 1		Indian Point 3	
Human Errors (XHEs) & Human Successes (HSs) Performance-Shaping Factors in Complexity	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS
Causal connections apparent (positive)												
Simultaneous tasks with high attention demands	1	1	3	1								
Extensive knowledge regarding the physical layout of the plant is required												
Coordination required between multiple people in multiple locations							10					
Demands to track and memorize information												
Ambiguous or misleading information present			1				1					
Information fails to point directly to the problem			1				13					
System dependencies are not well defined		1										
Scenario demands that the operator combine information from different parts of the process and information systems			1									
Loss of plant functionality complicates recovery path												
Presence of multiple faults			1									
Problems in differentiating important from less important information							32		18			
Other												
Worker distracted/ interrupted												
High number of alarms												
Weak causal connections exist			1				5					
General ambiguity of the event												
Dependencies well defined (pos)		1								1		
Few or no concurrent tasks (pos)										1		
Difficulties in obtaining feedback	1						7					
Complexity Sums	2	3	8	1	0	0	68	0	18	2	0	0

Event	Indian Point 2 (8/14/2003)		Ginna		Fermi 2		Fitz Patrick		Comanche Peak 2		Wolf Creek	
Human Errors (XHEs) & Human Successes (HSs) Performance-Shaping Factors in Complexity	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS	XHE	HS
Causal connections apparent (positive)												
Simultaneous tasks with high attention demands											4	
Extensive knowledge regarding the physical layout of the plant is required											1	
Coordination required between multiple people in multiple locations		1										
Demands to track and memorize information												
Ambiguous or misleading information present												
Information fails to point directly to the problem												
System dependencies are not well defined												
Scenario demands that the operator combine information from different parts of the process and information systems												
Loss of plant functionality complicates recovery path												
Presence of multiple faults						1						
Problems in differentiating important from less important information											2	
Other												
Worker distracted/ interrupted									1			
High number of alarms												
Weak causal connections exist											3	
General ambiguity of the event				1							4	1
Dependencies well defined (pos)												
Few or no concurrent tasks (pos)												
Difficulties in obtaining feedback												
Complexity Sums	0	1	0	1	0	1	0	0	1	0	14	1

Event	Diablo Canyon 1		Palo Verde 1 6/14/2004		Peach Bottom 2		Palo verde 1 7/30/2004		
Human Errors (XHEs) & Human Successes (HSs) Performance-Shaping Factors in Complexity	XHE	HS	XHE	HS	XHE	HS	XHE	HS	Complexity Type Totals
Causal connections apparent (positive)									5
Simultaneous tasks with high attention demands			11	3	1				48
Extensive knowledge regarding the physical layout of the plant is required		2				1			8
Coordination required between multiple people in multiple locations		3	4						19
Demands to track and memorize information									3
Ambiguous or misleading information present							4		11
Information fails to point directly to the problem			4						29
System dependencies are not well defined			1				8	1	17
Scenario demands that the operator combine information from different parts of the process and information systems			2						17
Loss of plant functionality complicates recovery path	1	2							7
Presence of multiple faults		2	5						10
Problems in differentiating important from less important information			2						62
Other									1
Worker distracted/ interrupted									3
High number of alarms			1						3
Weak causal connections exist					1				11
General ambiguity of the event									12
Dependencies well defined (pos)									2
Few or no concurrent tasks (pos)									1
Difficulties in obtaining feedback									8
Complexity Sums	1	9	30	3	2	1	12	1	277

Appendix D: STAMP Analysis

STAMP Analysis of Salem 1 Incident Based on HERA Database

Overview

On the morning of Thursday, April 7, 1994, the Salem Nuclear Power Plant was experiencing an intrusion of grass from the Delaware River in the intake structure for the circulating water (CW) system. As a result, the plant was not operating at full power and two off-duty supervisory staff members were positioned near the CW pumps to help restore them to service should they trip. The reactor operator was performing a number of tasks, including manually manipulating the control rods, adding boron as necessary, transferring electrical loads, and maintaining the control room log.

By 10:15 AM, the CW system screens had become so clogged that there was a significant water level drop across them and the weight of the grass was starting to cause shear pins to fail; a minute later, the water level drop had increased enough to cause the pumps to trip.

In response, the control room operators began to reduce the load across the turbines and increase the rate of turbine power reduction as high as 8% per minute. The Senior Nuclear Shift Supervisor (SNSS) left the control room area to help restart one of the CW pumps to try to prevent a turbine trip, leaving only the Nuclear Shift Supervisor (NSS) and two licensed operators in the control room. When the operators tried to turn this pump on after the SNSS had caused an override of a safety-locking feature, the pump tripped.

A series of alarms began to sound as the turbine load reduction finished. At this point, the reactor operator (RO) began to move the plant's electrical loads to offsite sources. While he was doing this, the NSS started to withdraw the control rods in response to indications of overcooling; however, when he told the RO to continue to raise reactor power (and thus temperature), he did not mention this fact and also did not provide specific enough instructions to allow the RO to correctly withdraw the rods. This led to a second trip of the CW pumps at 10:46 and a reactor trip at 10:47, which initiated an automatic safety injection (SI) that began to fill the pressurizer. In response, the operator stopped the SI, but not before the pressurizer had become solid. The steam generator (SG) pressure also began to increase, but the normal automatic relief system did not work properly, so an alternative automatic relief system actuated. This in turn led to enough of a decrease in primary pressure that there was another series of automatic safety injections, which could have led to an overpressure condition; however, the operators successfully took manual control of the pressure relief valves to prevent this.

At 1:16 PM, as a result of the malfunctioning of a number of automatic systems, including multiple trains of the safety injection system, plant management declared an Alert, which mobilized further resources to help the operators recover from the situation.

Subsequently, the operators restored the necessary systems and plant conditions to allow for a plant cool down. The Alert was terminated at 8:20 PM, and the plant entered Cold Shutdown at 11:24 AM the following morning.

Timeline of Events

	Control Room			Turbine Hall	Other
Time	**Reactor Operator**	**Balance of Plant Operator**	**Other**		
10:15 AM				Loads on the screens have become so heavy that shear pins are failing and there is a 1-1.5 foot drop in water level across the trash racks	
10:16 AM	Control rods switched to automatic	Begins turbine load reduction		Water level differential across screens reaches 10ft; 13B CW pump trips	
10:27 AM		Increases rate of turbine load reduction		13A CW pump trips	
approx. 10:32 AM		Increases rate of turbine load reduction as high as 8% per minute		13B CW pump trips	
10:33 AM	Control rods switched back to manual control		SNSS leaves control room	SNSS manually lifts contacts on 12A CW pump water box to override protective interlock	
10:34 AM			Operators try to restart 12A CW pump	12A CW pump trips again	
10:37 AM	Trying to reduce reactor power and temperature and add boron as necessary				
10:39 AM			Operators restart 13A and 13B CW pumps	13A and 13B CW pumps back on	

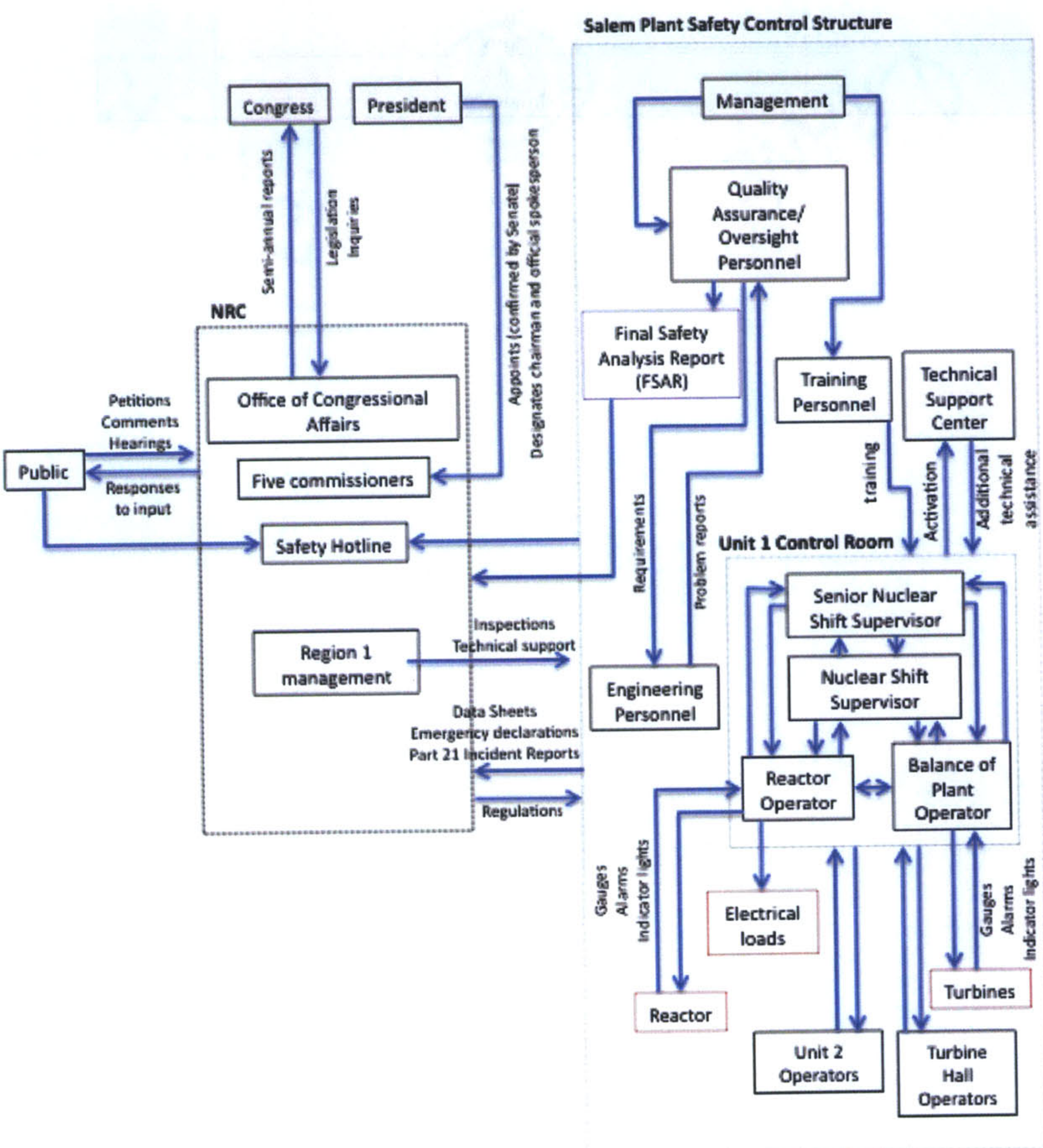
10:40 AM			Low-low condenser vacuum alarm activates		
10:42 AM		Idles a feedwater pump			
10:43 AM	Begins to switch onsite electrical loads to offsite power supplies	Load reduction complete			
10:44 AM			Low-low Tave bistables trip		
10:45 AM	Finishes switching electrical loads; begins to withdraw control rods; notices Tave is below minimum critical temperature; monitors Tave (but not reactor power)		NSS begins to withdraw control rods, then stops and tells RO to do so		
10:46 AM				13A and 13B CW pumps trip again	
10:47 AM			Reactor trips; automatic SI on train A; ECCS pumps start; main feedwater regulating valves close		
10:49 AM	Enter procedure 1-EOP-TRIP-1 (Reactor Trip or Safety Injection)				
10:53 AM			Manually initiate main feedwater isolation		

10:58 AM			Primary coolant temperature begins to increase; manually initiate main steam isolation and reposition components to expected positions; manually trip main feed pumps		Declaration of Unusual Event
11:05 AM			Reset SI Train A with automatic actuation in "blocked" condition		
11:10 AM			Transition to procedure 1-EOP-TRIP-3 (Safety Injection Termination)		
11:15 AM			Fix incorrectly positioned letdown isolation valve		
11:23 AM			Pressurizer is solid; power operated relief valves (PORVs) open to relieve water to Pressurizer Relief Tank (PRT)		

11:26 AM			Two SG safety valves lift to release built-up steam; automatic SI actuated; initiate manual SI		
11:30 AM			Plant in solid plant pressure control		
11:43 AM	Controlling reactor coolant system via main steam atmospheric relief valves and chemical and volume control system; enters Technical Specification Action Statement 3.0.3 because of two blocked automatic SI trains		Both SI trains locked and unavailable		
12:54 PM			Number 11 main steam relief valve opens halfway, but is immediatel y closed		
1:16 PM	Begin heatup of pressurizer				Alert declared
1:36 PM					NRC enters monitori ng phase of Normal Response Mode of Incident Response Plan
2:10 PM	Reestablished steam space in pressurizer				Technica l Support Center staffed to assist operators
4:30 PM	Restored pressurizer level to 50%				

5:15 PM			Plant cooldown starts		
8:20 PM					Alert ends
1:06 AM			Hot shutdown		
11:24 AM			Cold shutdown		

Safety Control Structure



On the left half of the diagram, the control structure connected with the NRC is shown. While some of the internal structures are present, most are not directly relevant to this incident, so beyond this point, this entire section will be considered a single entity and referred to as the NRC.

On the right of the diagram are the most important aspects of the plant's safety control structure with respect to this incident. Although the plant has two units, this incident primarily concerned Unit 1, so the emphasis is placed on the Unit 1 control room in this diagram. Personnel are outlined in black, reports are outlined in purple, and equipment is outlined in red.

STAMP Analysis

NRC

Safety Requirements and Constraints Violated

- none

Inadequate Decisions and Control Actions

- none

Inadequate Controls

- none

Context

- Given incomplete information by plant's communicator

Inadequate Communication and Coordination

- Given incomplete information by plant's communicator

Mental Model Flaws

- none

Plant Management

Safety Requirements and Constraints Violated

- Must fix problems in a timely manner
- Must promptly identify and correct significant conditions adverse to quality
- Must provide adequate training, guidance, and procedures to deal with grass transients, solid pressurizers, and plant operation with the reactor temperature below the minimum necessary for critical operation
- Must adequately understand and emphasize safety aspects of tasks (safety first)
- Must provide management expectations in operating procedures for when operators should stop trying to keep the plant running and trip the reactor or turbines
- Must ensure that Notification of Unusual Event to NRC contains all relevant and important information

Inadequate Decisions and Control Actions

- Allowed for (and sanctioned) degraded conditions and workarounds

Inadequate Controls

- Inadequate rules

Context

- Grass intrusions and resulting reactor power transients were seen as routine

Inadequate Communication and Coordination

- Failed to clearly express expectations for staff performance

Mental Model Flaws

- Saw grass intrusions and resulting reactor power transients as routine
- Did not appreciate importance of safety
- Accepted degraded conditions and workarounds

Quality Assurance/Oversight Personnel

Safety Requirements and Constraints Violated

- Must revise FSAR and conduct complete safety evaluation when making changes
- Must promptly identify and correct significant conditions adverse to quality
- Must provide adequate training, guidance, and procedures to deal with grass transients, solid pressurizers, and plant operation with the reactor temperature below the minimum necessary for critical operation
- Must provide management expectations in operating procedures for when operators should stop trying to keep the plant running and trip the reactor or turbines

Inadequate Decisions and Control Actions

- Allowed for degraded conditions and workarounds

Inadequate Controls

- Inadequate rules

Context

- Grass intrusions and resulting reactor power transients were seen as routine

Inadequate Communication and Coordination

- none

Mental Model Flaws

- Saw grass intrusions and resulting reactor power transients as routine
- Accepted degraded conditions and workarounds

Technical Support Center

Safety Requirements and Constraints Violated

- none

Inadequate Decisions and Control Actions

- none

Inadequate Controls

- none

Context

- Unusual Event and Alert declared

Inadequate Communication and Coordination

- none

Mental Model Flaws

- none

Training Personnel

Safety Requirements and Constraints Violated

- Must provide adequate training to deal with grass transients, solid pressurizers, and plant operation with the reactor temperature below the minimum necessary for critical operation
- Must adequately emphasize safety aspects of tasks (safety first)
- Must explain importance of "Yellow Path" procedures

Inadequate Decisions and Control Actions

- none

Inadequate Controls

- none

Context

- none

Inadequate Communication and Coordination

- none

Mental Model Flaws

- Did not appreciate importance of safety

Engineering Personnel

Safety Requirements and Constraints Violated

- Must promptly identify and correct significant conditions adverse to quality
- Must restore 12A pump circuit breaker after maintenance

Inadequate Decisions and Control Actions

- none

Inadequate Controls

- Insufficient instrumentation available to detect cause of issues

Context

- none

Inadequate Communication and Coordination

- none

Mental Model Flaws

- none

Senior Nuclear Shift Supervisor

Safety Requirements and Constraints Violated

- Must remain in control room to assist during transients
- Must adequately emphasize safety aspects of tasks (safety first)
- Must adhere to procedures
- Must remain in supervisory role

Inadequate Decisions and Control Actions

- Allowed for degraded conditions and workarounds
- Left control room during transient

Inadequate Controls

- none

Context

- Plant operating below full power
- 12A CW pump out of service; other CW pumps tripped during incident
- Many distractions in control room
- Needed to remain in communication with CW operators, Unit 2 operators, and turbine hall operators

Inadequate Communication and Coordination

- Failed to adequately reinforce management expectations for staff performance

Mental Model Flaws

- Did not appreciate importance of safety
- Saw trip of reactor or turbines as last resort only
- Saw grass intrusions and resulting reactor power transients as routine
- Accepted degraded conditions and workarounds
- Did not recognize importance of "Yellow Path" procedures

Nuclear Shift Supervisor

Safety Requirements and Constraints Violated

- Must maintain supervisory role
- Must communicate any changes in control rod status to RO
- Must give RO adequate instructions to increase reactor power

Inadequate Decisions and Control Actions

- Allowed for degraded conditions and workarounds
- Did not tell RO that rods had been manipulated

Inadequate Controls

- Inadequate rules
- Initially failed to notice overcooling reactor
- Initially missed alignment of one isolation valve

Context

- Plant operating below full power
- 12A CW pump out of service; other CW pumps tripped during incident
- Senior supervisor in control room once SNSS left
- Many distractions in control room
- Needed to remain in communication with CW operators, Unit 2 operators, and turbine hall operators
- Understaffed control room, especially once SNSS left
- Reactor trip
- Logic disagreements between SI trains
- Unusual Event and Alert declared
- Solid pressurizer
- Automatic function of main steam valves (MS10s) didn't work properly

Inadequate Communication and Coordination

- Failed to adequately reinforce management expectations for staff performance
- Failed to tell RO he had manipulated control rods
- Failed to give RO adequate guidance during reactor power increase

Mental Model Flaws

- Did not appreciate importance of safety
- Saw trip of reactor or turbines as last resort only
- Saw grass intrusions and resulting reactor power transients as routine
- Accepted degraded conditions and workarounds
- Did not recognize RCS heatup or SG pressure increase
- Reactive rather than proactive mode – followed procedures, but did not see "big picture"
- Did not recognize importance of "Yellow Path" procedures

Reactor Operator

Safety Requirements and Constraints Violated

- none

Inadequate Decisions and Control Actions

- Did not mention reactor overcooling to NSS
- Monitored Tave rather than reactor power while raising reactor power

Inadequate Controls

- Inadequate rules
- Initially failed to notice overcooling reactor
- Initially missed alignment of one isolation valve
- Did not recognize RCS heatup or SG pressure increase

Context

- Unreasonable and unclear management expectations
- Given no additional assistance, even though grass transients were expected
- Control rods were under manual control
- Plant operating below full power
- 12A CW pump out of service; other CW pumps tripped during incident
- Needed to manually keep reactor power comparable to turbine power despite abnormally high turbine load reduction rate
- Many distractions in control room
- Management pressure to avoid reactor trip
- Overburdened – in charge of rod control, boron additions, electrical load transfer, control room log, and reading procedures to BOP operator when necessary
- Needed to remain in communication with CW operators, Unit 2 operators, and turbine hall operators
- Understaffed control room, especially once SNSS left
- Reactor trip
- Logic disagreements between SI trains
- Unusual Event and Alert declared
- Solid pressurizer

Inadequate Communication and Coordination

- Failed to point out reactor overcooling to NSS

Mental Model Flaws

- Saw trip of reactor or turbines as last resort only
- Saw grass intrusions and resulting reactor power transients as routine
- Reactive rather than proactive mode – followed procedures, but did not see "big picture"
- Did not recognize importance of "Yellow Path" procedures

Balance of Plant Operator

Safety Requirements and Constraints Violated

- none

Inadequate Decisions and Control Actions

- Went to abnormally high turbine load reduction rate (8%)
- Did not pay enough attention to increasing SG pressure

Inadequate Controls

- Inadequate rules
- Initially failed to notice overcooling reactor
- Initially missed alignment of one isolation valve
- Did not recognize RCS heatup or SG pressure increase

Context

- Unreasonable and unclear management expectations
- Given no additional assistance, even though grass transients were expected
- Plant operating below full power
- 12A CW pump out of service; other CW pumps tripped during incident
- Many distractions in control room
- Management pressure to avoid reactor trip
- Needed to remain in communication with CW operators, Unit 2 operators, and turbine hall operators
- Understaffed control room, especially once SNSS left
- Reactor trip
- Logic disagreements between SI trains
- Unusual Event and Alert declared
- Solid pressurizer
- Responsible for conducting actions read by RO from procedures
- Automatic function of main steam valves (MS10s) didn't work properly

Inadequate Communication and Coordination

- none

Mental Model Flaws

- Saw trip of reactor or turbines as last resort only
- Saw grass intrusions and resulting reactor power transients as routine
- Reactive rather than proactive mode – followed procedures, but didn't see "big picture"
- Didn't recognize importance of "Yellow Path" procedures

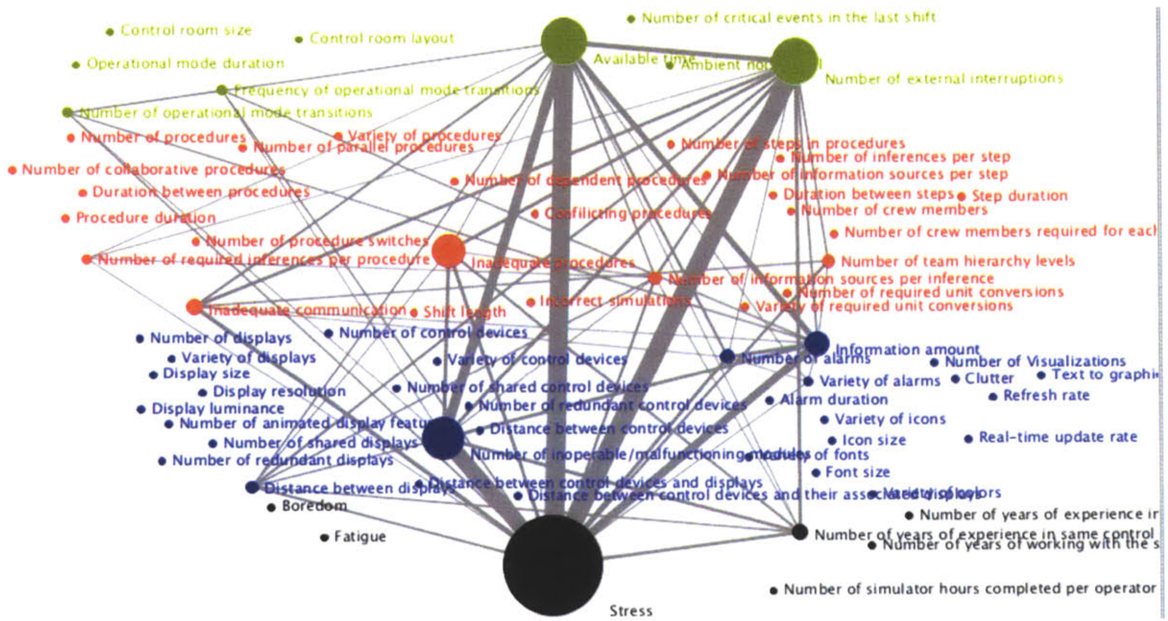
Conclusions and Recommendations

Many of the root causes of the Salem incident ultimately stemmed from improper mindsets and attitudes. There was a strong focus on continued production and operation and an acceptance of workarounds to avoid paying for proper maintenance, even if this might pose a safety risk. Operators were trained just effectively enough to be able to follow specific procedures, but were not given sufficient training to be able to really understand situations. In most cases, this level of training was sufficient since the operators only really needed to be able to find the correct procedures based on the plant state; however, in this instance, it kept the crew from more effectively dealing with some of the issues and led to some of the complications in this event.

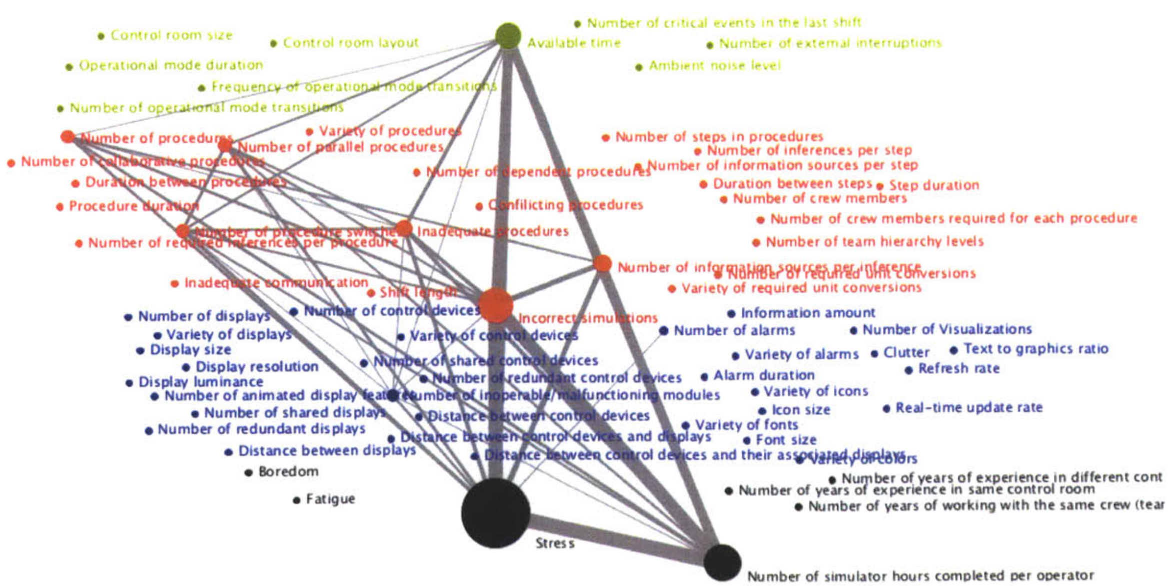
What follows is a list of some recommendations for improvement based on this analysis. First, there needs to be a shift away from the current mindset to do everything possible to keep the plant running at all times, even at the expense of safety. Operators need to be made aware of situations in which it might be safer to trip the reactor and turbines and trained to think of this as a possible course of action. Second, management needs to be willing to spend the money to properly fix significant issues in order to ensure the continued safe operation of the plant; if necessary, the NRC should impose time limits on how long a licensee can wait to fix a problem once it has been found. Third, management should understand that just because an event happens often does not make it "routine" and that some recurring situations, like the grass transient, should really be treated as emergency situations. Operators should be given sufficient training to be able to understand and correct the causes of issues that could arise during these events rather than just enough to let them compensate for systems lost as a result of these issues, particularly if they are expected to consistently make decisions on an ad hoc basis. Still, operators need to be aware that they should follow procedures except in exceptional circumstances, since the procedures are generally the most reliable way to deal with an issue. There should also be extra help available to the control room to ensure that all critical systems can continue to be monitored even if additional emergency actions need to be taken, and operators should be aware which systems need to be monitored most closely. Operators should be aware of instances in which there might be multiple acceptable procedures or what to do if there don't seem to be any perfect procedures and how to use systems like the "yellow path". Fourth, operators should be encouraged to ask for clarification if they have any questions at all about directions they were given and encouraged to keep constantly open lines of communication among the people in the control room, especially if one person alters something that impacts the systems under someone else's care. Fifth, there should be stronger double checks to ensure that all procedures are carried out and completed correctly, including both operating room procedures and maintenance procedures. Finally, the people responsible for contact with the NRC need to be aware what information the NRC needs to in order to be helpful and not simply default to providing the minimum possible amount of information.

Appendix E: CSNs for HERA Incidents

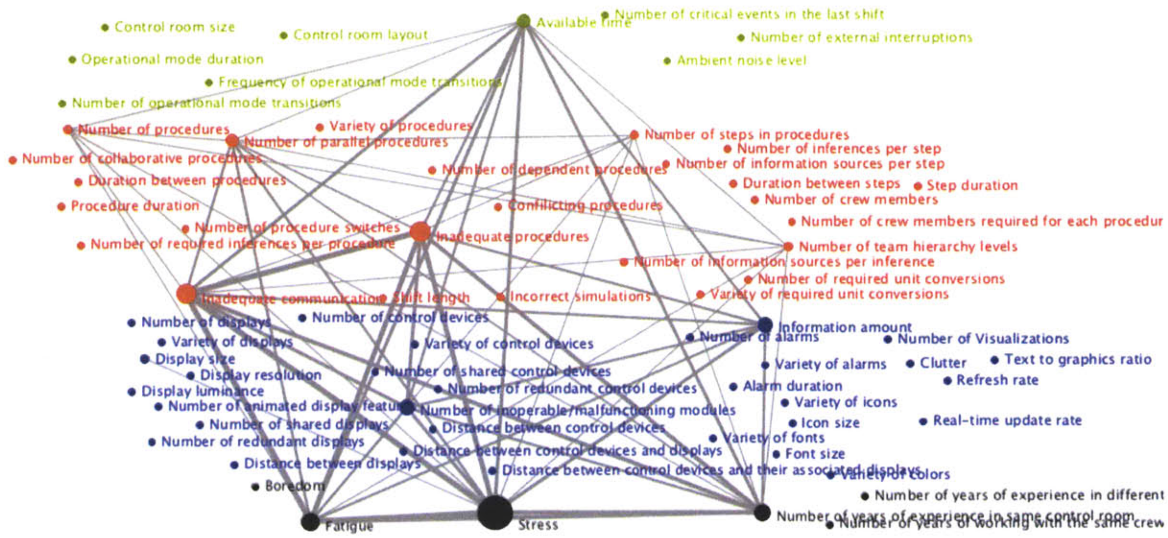
Browns Ferry 1



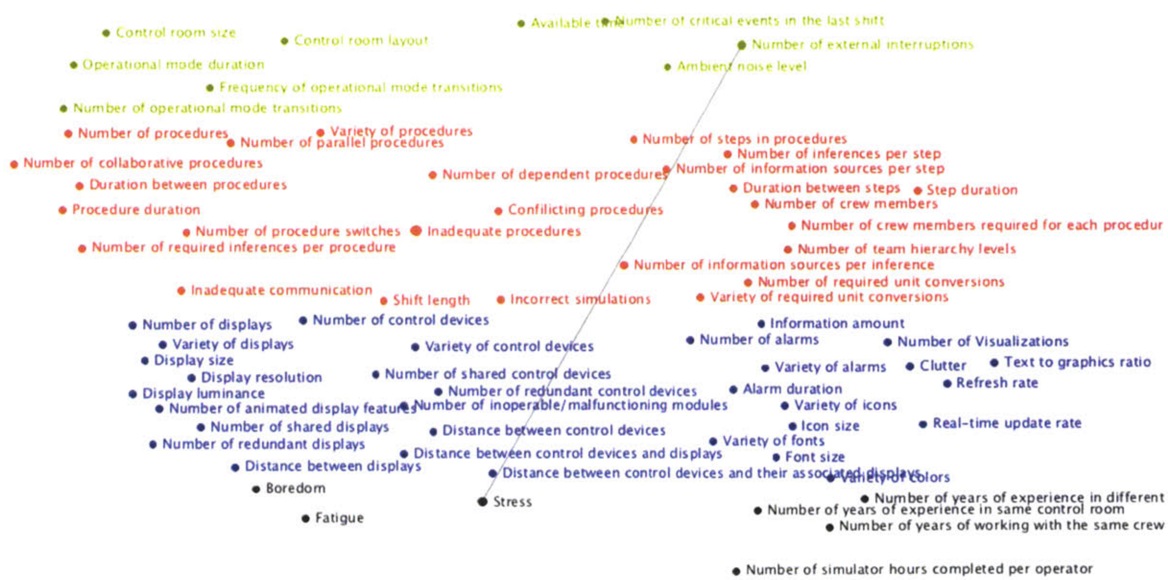
Calvert Cliffs 1



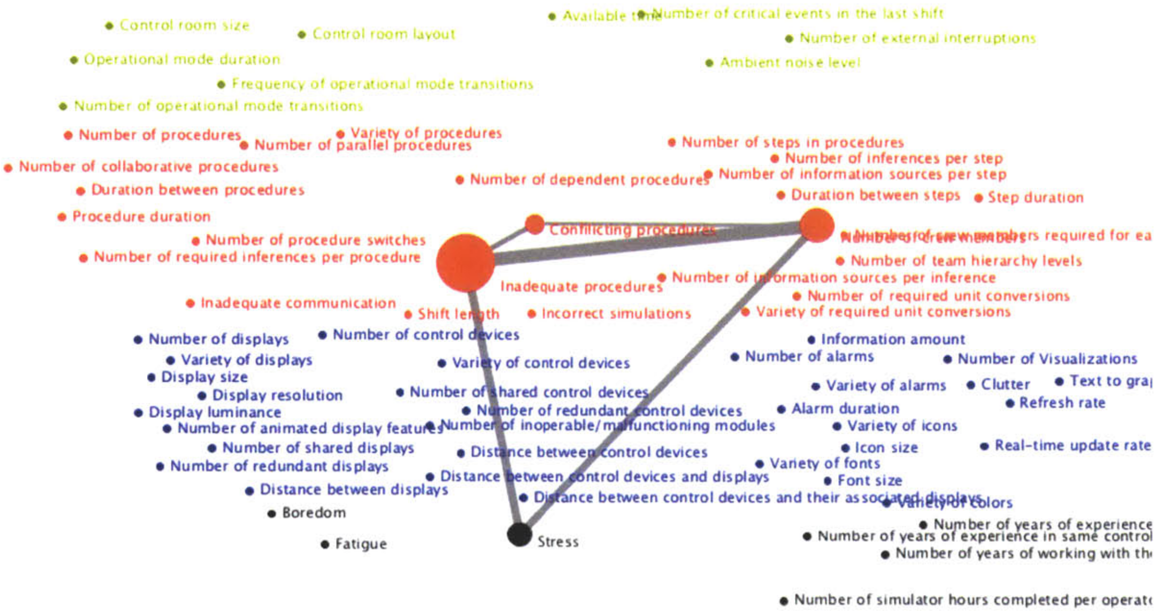
Crystal River 3



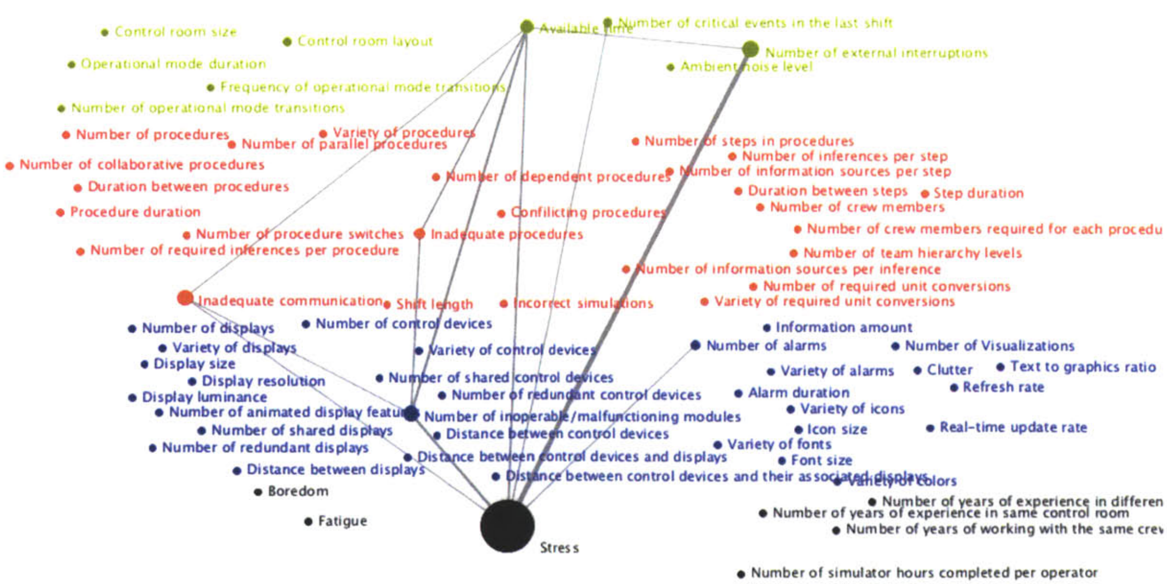
Comanche Peak 2



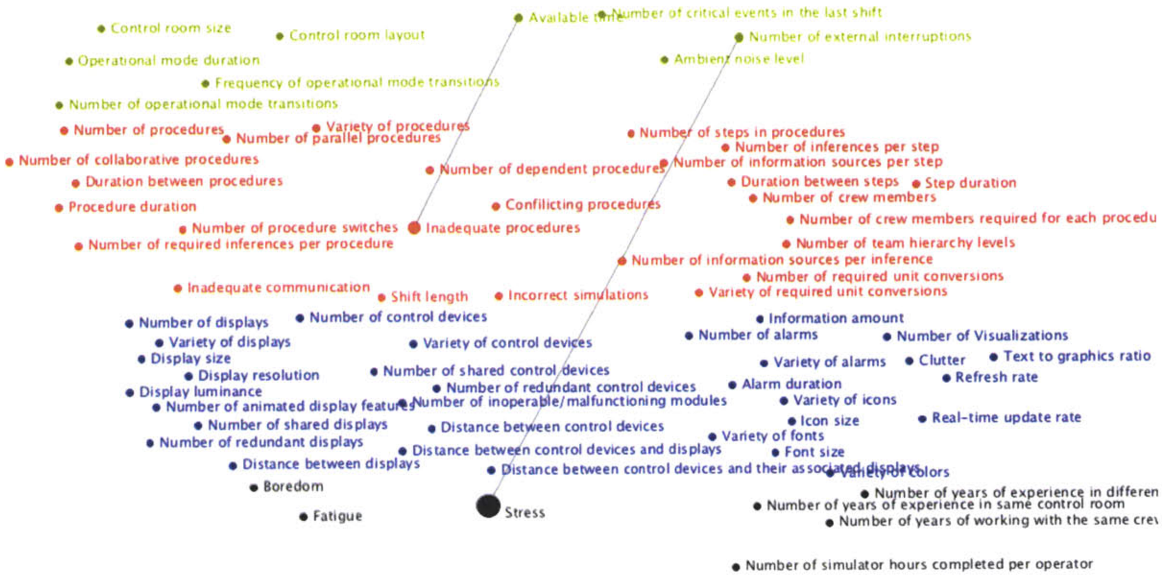
Davis-Besse



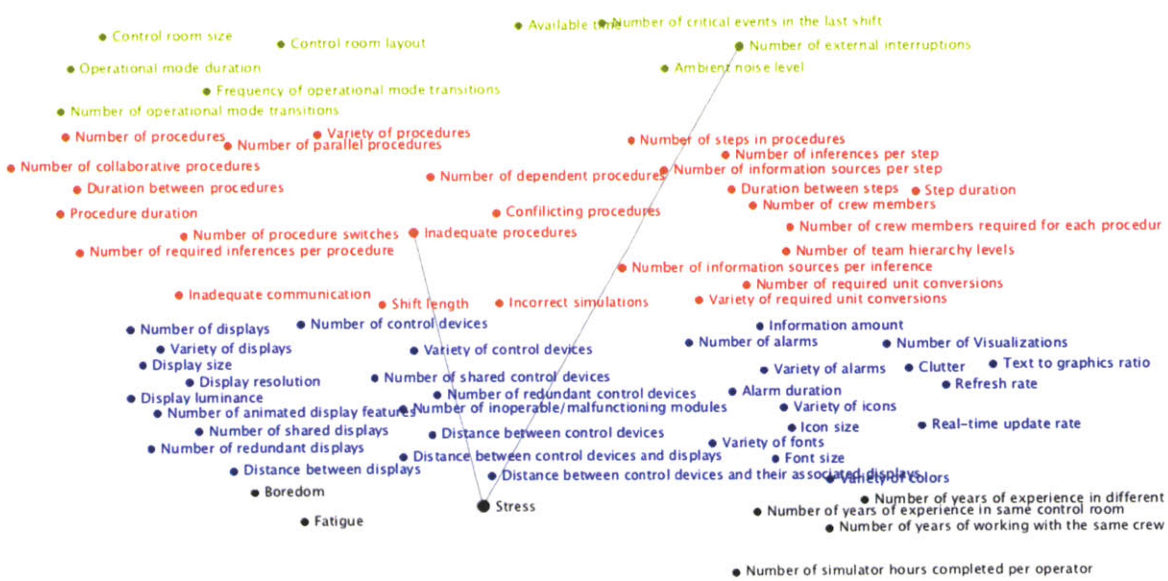
Diablo Canyon 1



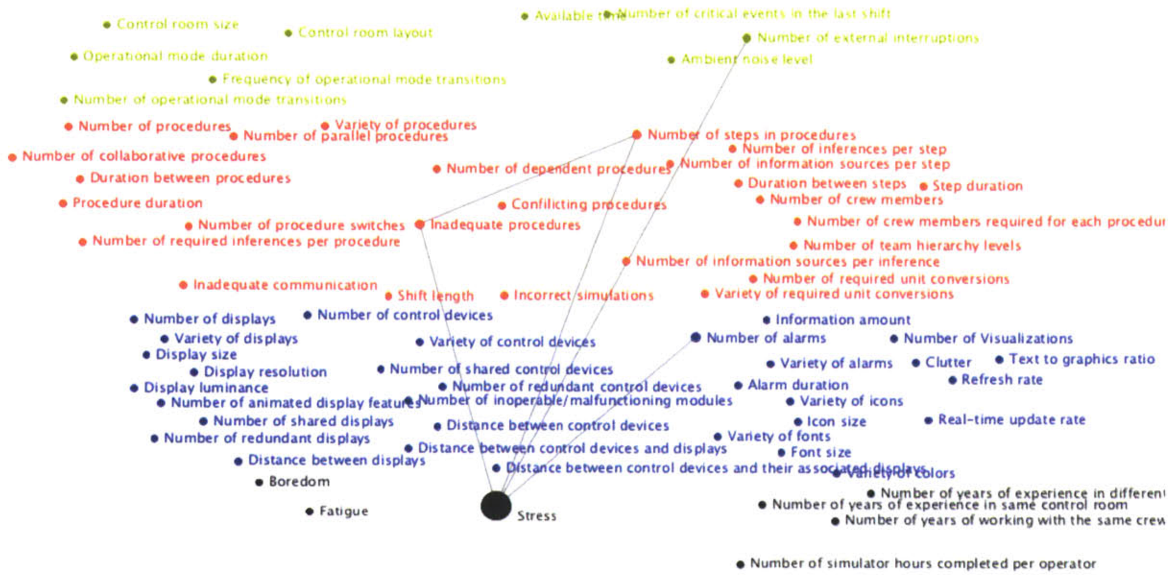
Fermi 2



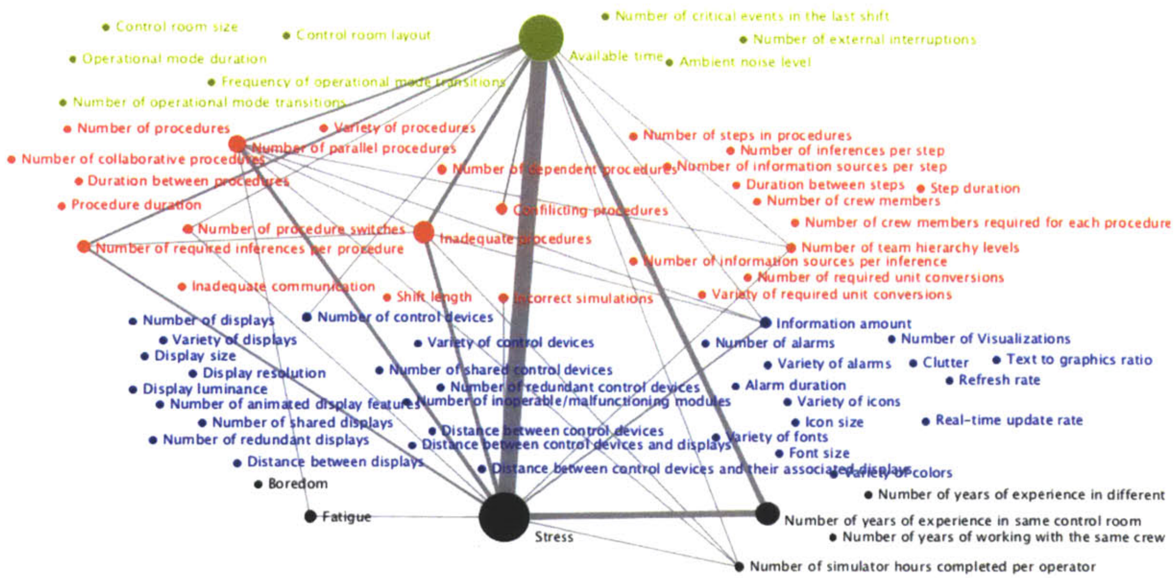
Fitz Patrick



Ginna

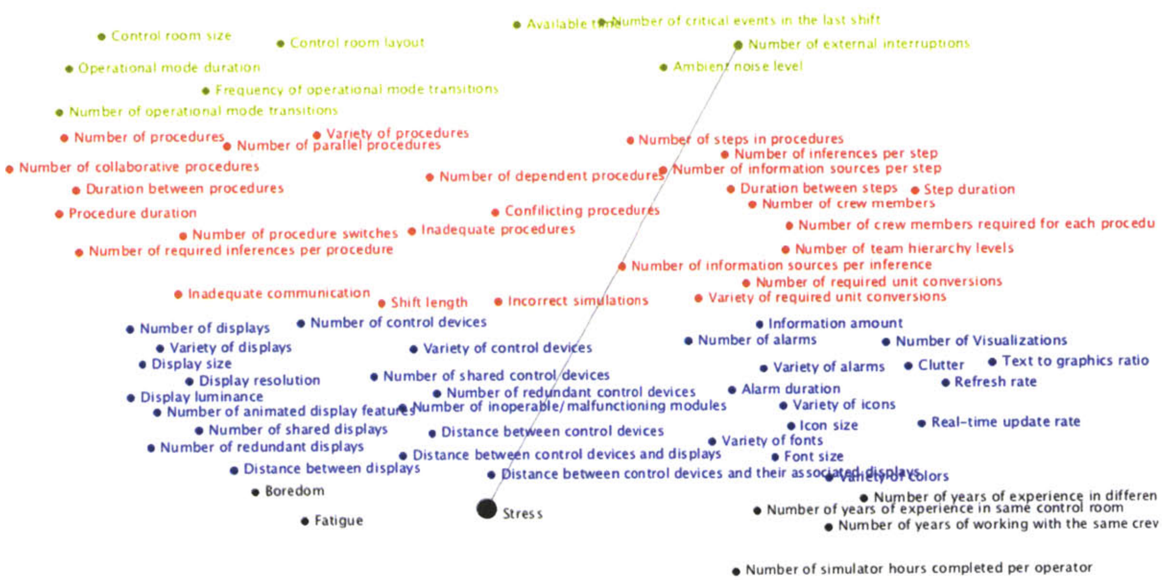


Indian Point 2 (1)

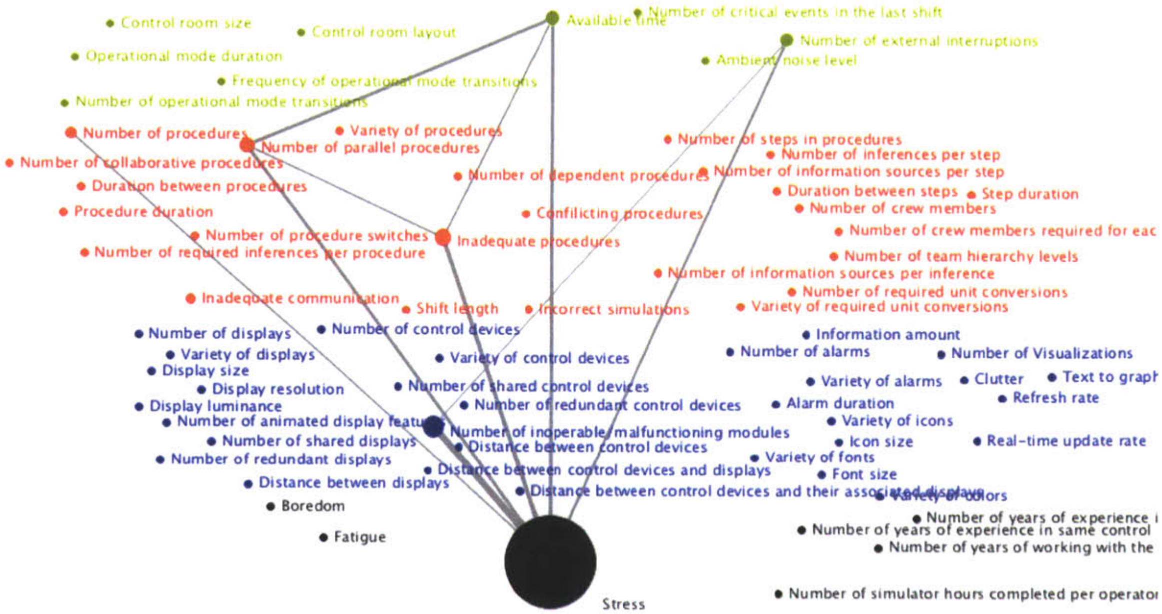


Indian Point 2 (2)

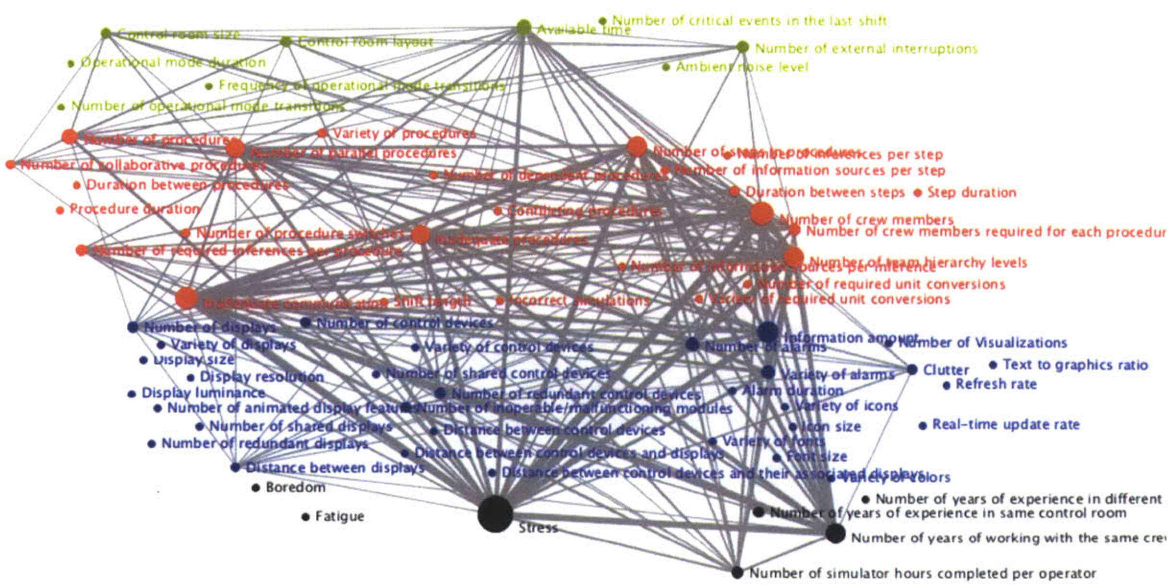
Indian Point 3



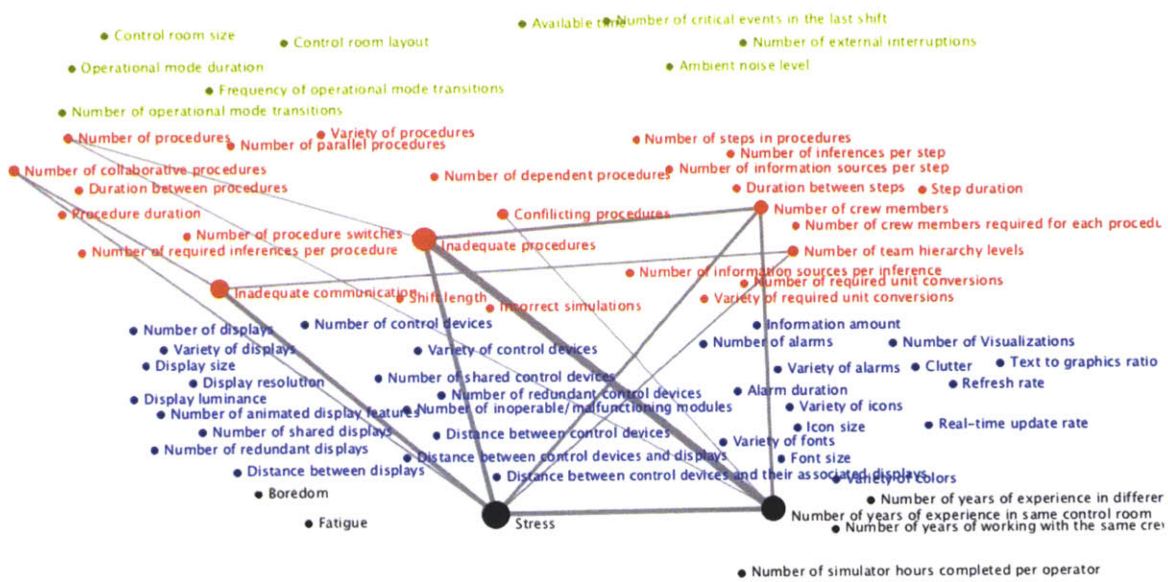
Le Salle 2



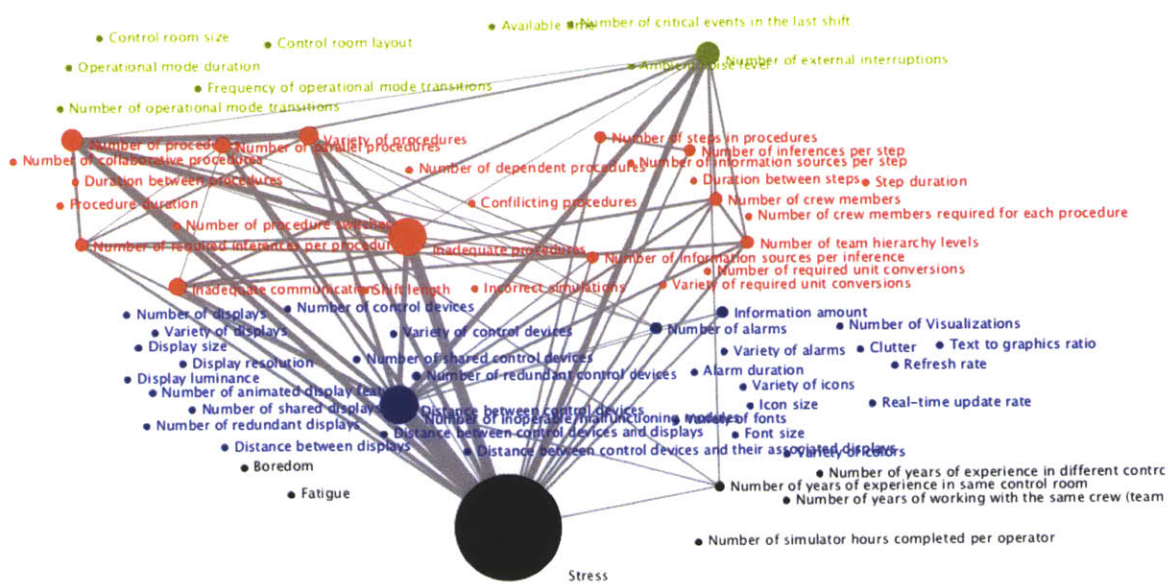
North Anna 1



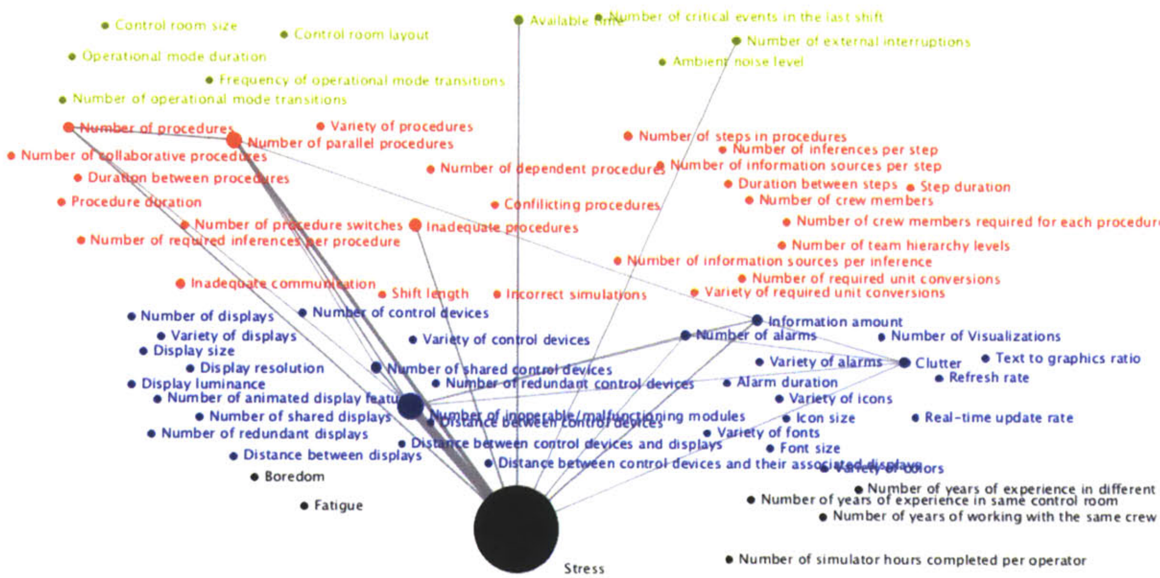
Palo Verde 1



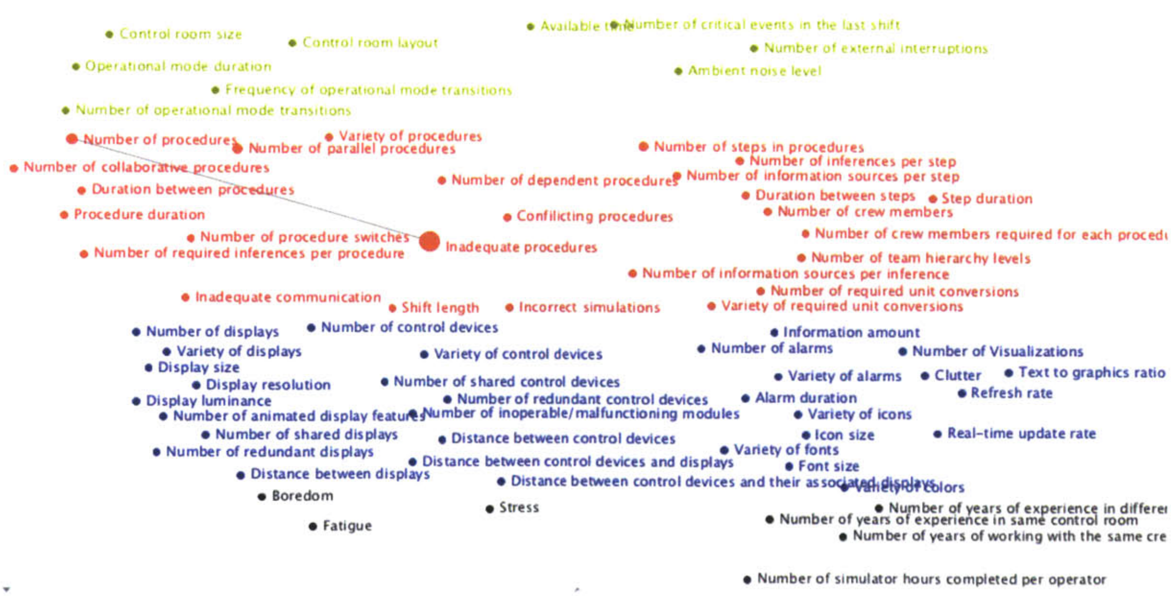
Palo Verde (2)



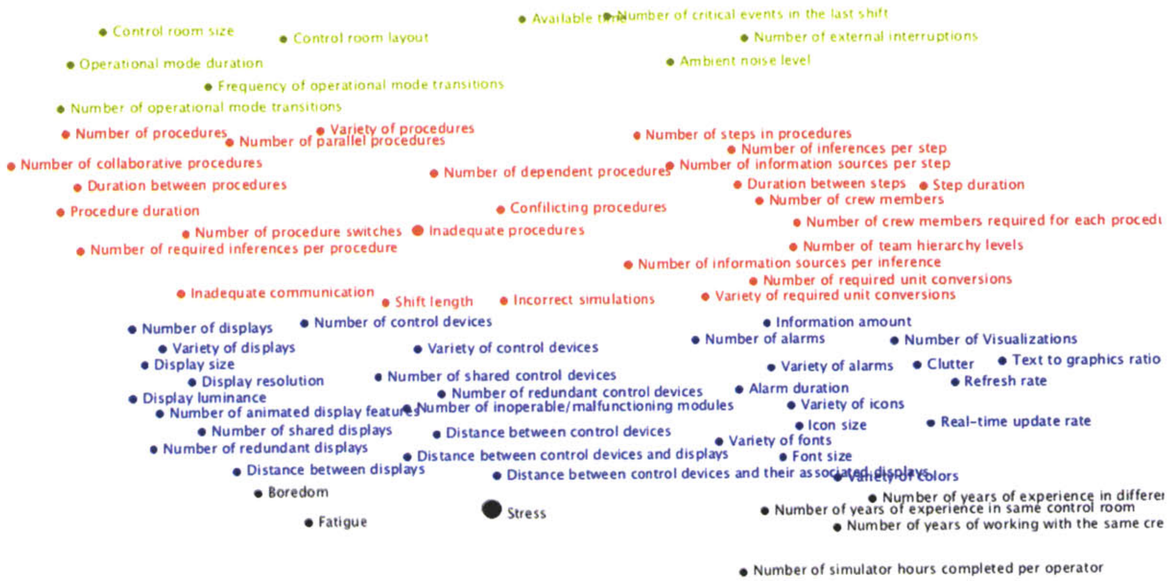
Peach Bottom 2



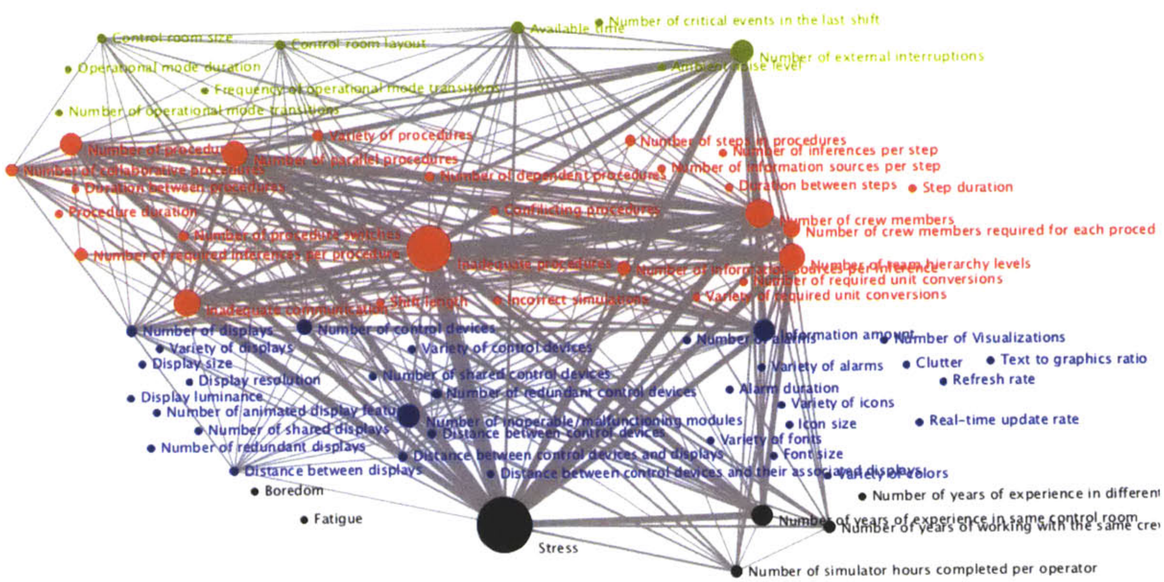
Point Beach 1



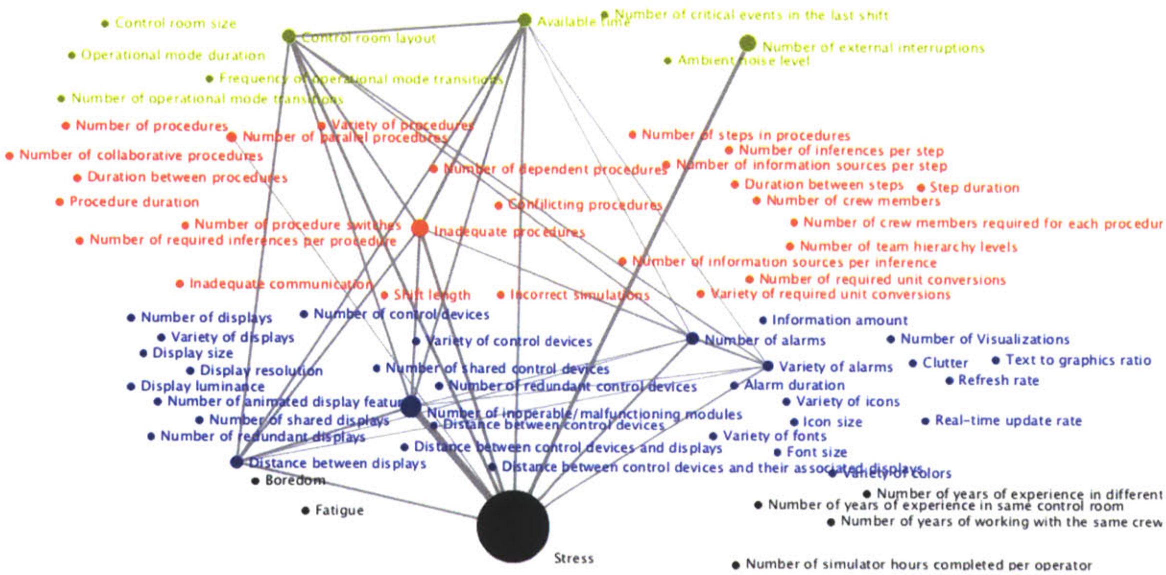
Quad Cities 2



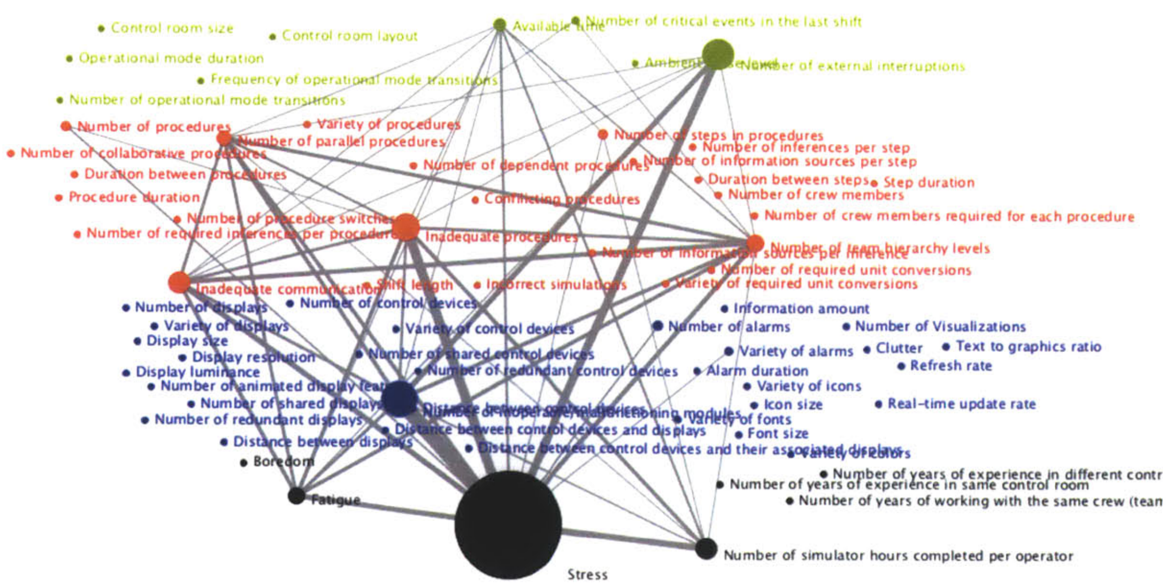
Salem 1



Waterford 3



Wolf Creek



Appendix F: CXViz (Complexity Visualization) User Guide

CXViz (Complexity Visualization) is an interactive network visualization and analysis tool based on the Graph Exploration System (GUESS) (Eytan, 2006; Eytan and Miryung, 2007), adapted to specifically to analyze Complexity Source Networks (CSNs). This system was implemented in a language called Jython (an implementation of Python for Java Virtual Machine (JVM)). Two versions of the system were developed: 1) Developer version. This version is a desktop application to let the researcher edit the sources of complexity and update the evidence database, and 2) View-only version. This version is an applet that was uploaded to MIT Humans and Automation Laboratory's (HAL) website[4] to let NRC researchers and other lab affiliates to view and interact with the software.

CXViz interface can be broken down into five main sections (Figure 33):

- Menu bar
- Vertical toolbar
- Database window
- Visualization window
- Side-by-side network displays (not shown in Figure 33)

The following sub-sections discuss each section in more detail.

F.1: The Visualization Window

This is the main window of the system, which displays the nodes and links of the network. While it is arguably the most important feature of the system, it has little functionality and is mainly used to visualize the network under investigation.

Graph element modification: right-clicking on a node or link allows the user to either modify its properties or remove it (Figure 34).

[4] http://web.mit.edu/aeroastro/labs/halab/cxviz.shtml

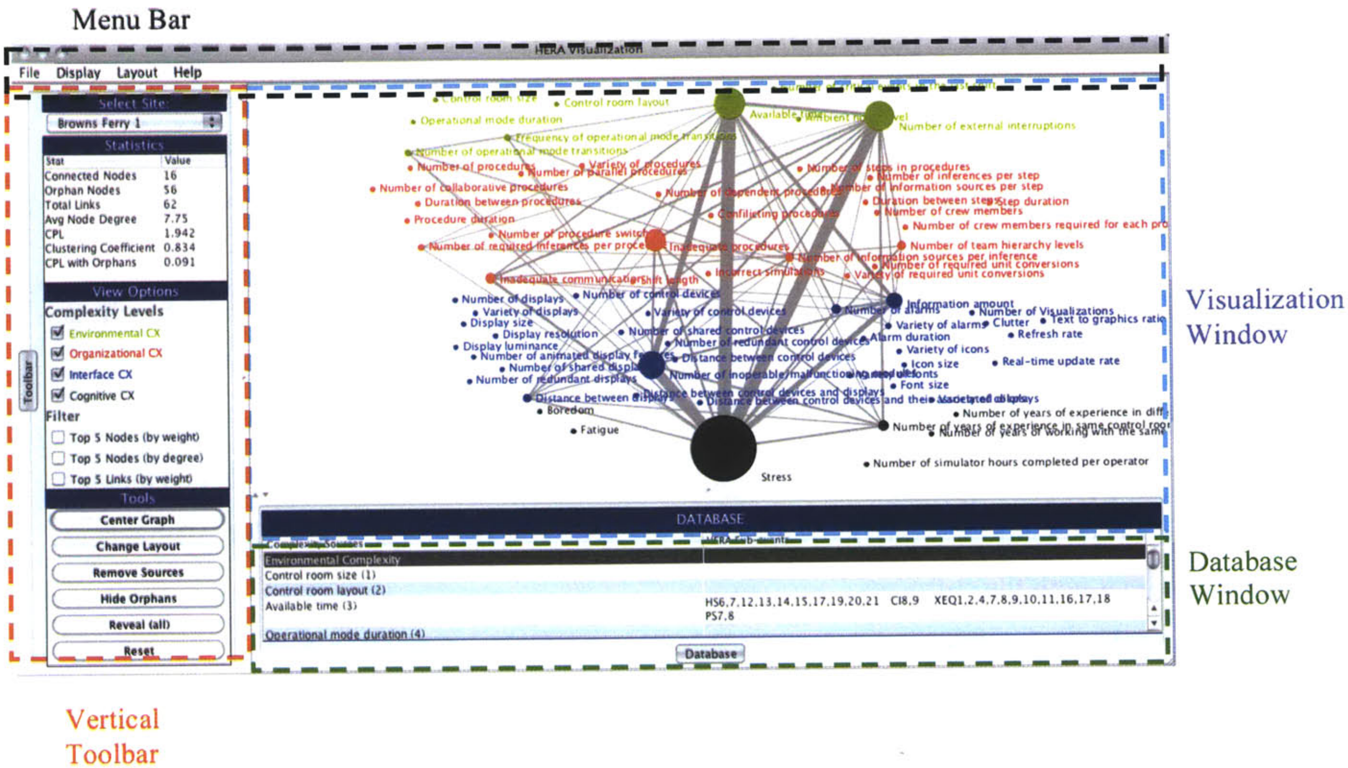


Figure 33. The CXViz interface.

Removing a node or link in this way removes it permanently and the user can only get it back by re-loading the data (by hitting the "Refresh" button, choosing an "Original" layout, or selecting the site again from the Site Selection box). Every time a change is made to the CSN, the statistics table will be updated to reflect these removed nodes and links.

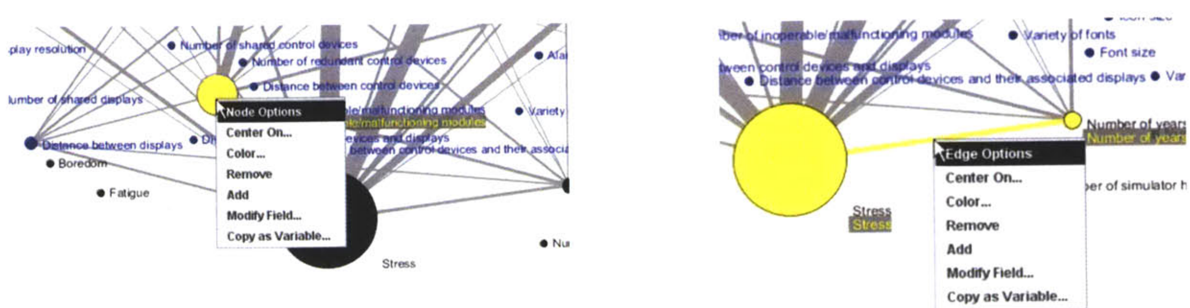


Figure 34. Modifying nodes (left) or links (right)

F.2: The Menu Bar

The menu bar appears at the very top of the applet and contains the following menu headers: File, Display, Layout, and Help (Figure 35).

Figure 35. Menu bar

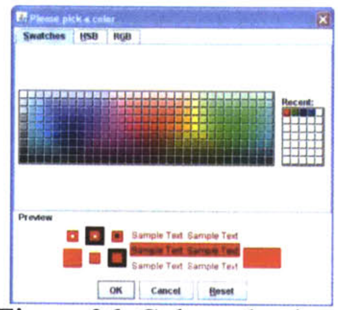


Figure 36. Color selection

File

- **Exit:** This closes the applet popup window.
- **Save:** Saves changes to the current CSN.

Display

- **Center**: Centers the network currently displayed in the visualization window.
- **Background Color**: Brings up a color selection window that allows the user to select the desired background color of the visualization window (Figure 36).

Layout

When the user selects an incident using the site selector, CXViz uses the embedded complexity chain to visualize the network. In order to enable the user to choose a layout algorithm to impose on the currently loaded network, several graph layout algorithms are provided (Figure 37). Currently, ten algorithms are provided. These are Bin Pack, GEM, Circular, Physics, Kamada-Kawai, Fruchterman-Rheingold, Spring, MDS, Random and Radial. Table 11 summarizes the definition of each algorithm.

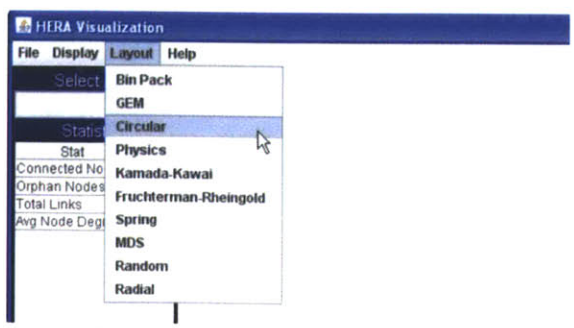
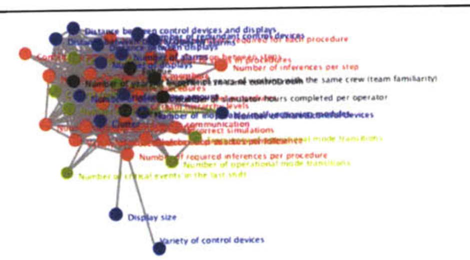
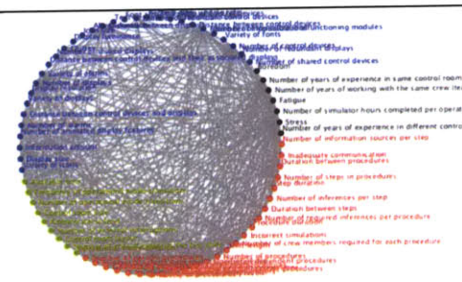
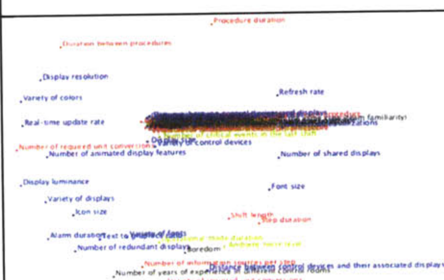
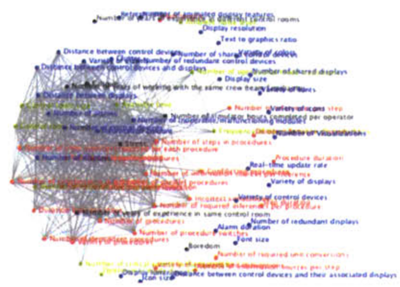
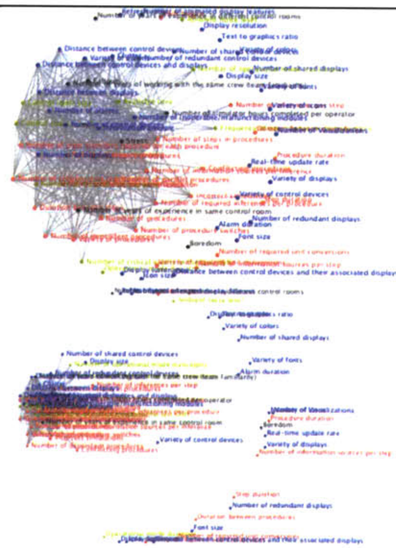
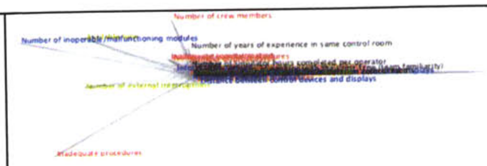
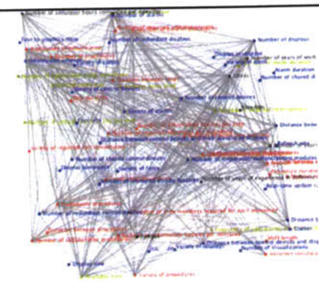
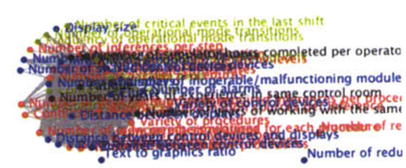


Figure 37. Layout algorithms

Table 11. Algorithms used for network layouts.

Algorithm	Definition	Sample
Bin Packing	Nodes of different degrees must be packed into a finite number (in this case 2) of bins (i.e., groups) of a certain capacity in a way that minimizes the number of bins used. This algorithm could be used to separate the nodes with no connection (i.e., orphan nodes).	
GEM	A tree generation algorithm that could be used to minimize the link intersections.	
Circular	Outer planar drawing algorithm that uses the smallest possible number of crossings.	
Physics	A type of force-directed (Spring) algorithm in which the forces are physics-based (i.e., nodes with certain properties, in this case those with links, attracts each other). This algorithm could be used to visualize the large component (the connected part) of the network.	

Kamada-Kawai	The Kamada-Kawai Algorithm is a force directed layout algorithm, which considers a force between any two nodes. In this algorithm, steel rings represent the nodes and the edges are springs between them. The attractive force is analogous to the spring force and the repulsive force is analogous to the electrical force. The basic idea is to minimize the energy of the system by moving the nodes and changing the forces between them. This algorithm produces a graph where edges have more or less equal length.	
Fruchteman-Rheigold	The Fruchterman-Reingold Algorithm is another type of force-directed layout algorithm, which considers a force between any two nodes. In this algorithm, steel rings represent the nodes and the edges are springs between them. The attractive force is analogous to the spring force and the repulsive force is analogous to the electrical force. The basic idea is to minimize the energy of the system by moving the nodes and changing the forces between them. This algorithm promotes a view that minimizes unnecessary intersections.	
Spring	The Spring Layout Algorithm is the simplest force-directed layout algorithm. The antigravity effect separated the connected nodes from the orphan nodes.	

MDS (Multidimensional Scaling)	This algorithm uses the weight attribute of links to define their lengths. Using this algorithm, the main interactions (in terms of weight) can be easily identified in a highly connected network.	
Random	Randomly lays out nodes while minimizing the collision between the nodes. This algorithm could be used to clearly view nodes in a cluttered CSN.	
Radial	Places the center node in the center and places nodes connected to it at increasing radii based on shortest path. Using this algorithm, the interactions for a specific source could be analyzed.	
Source: Börner et al. (2003); Weimao and Börner (2005), and Network Workbech (http://nwb.slis.indiana.edu)		

Help

- **Error Log**: In case of a bug in the program, this item brings up the stack trace of the error. Sending a copy of this trace, as well as a description of what was being done at the time of the error, back to the developer allows for fast bug fixes automatically (Figure 38).

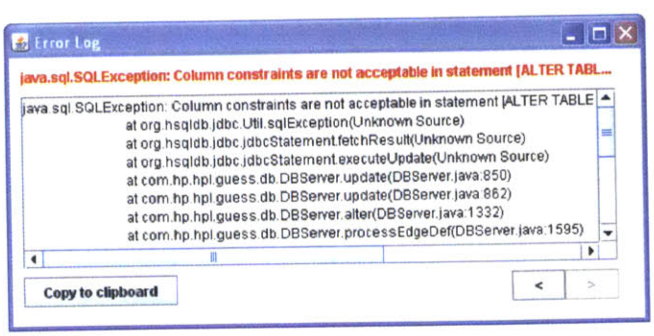


Figure 38. Error log window

Other functionalities such as a searchable help function are under development and will be added in the future.

F.3: The Vertical Toolbar

This vertical panel on the left side of the applet in Figure 33 contains most of the data-manipulation tools available to the user. It allows the user to change the level of details displayed, view simple statistics of the currently loaded graph, and choose from view options that hide or reveal categories of nodes, and manipulate the display or individual nodes.

Site Selector

Site selector provides a list of incidents in HERA plus the Three Mile Island incident. The user may choose from this list by clicking anywhere in the selection box, then scrolling to and clicking the desired site. This list includes data collected for 22 nuclear power sites as well as 6 different versions of the aggregate network that includes the aggregate of all the possible links and nodes and their aggregate weights (Figure 39).

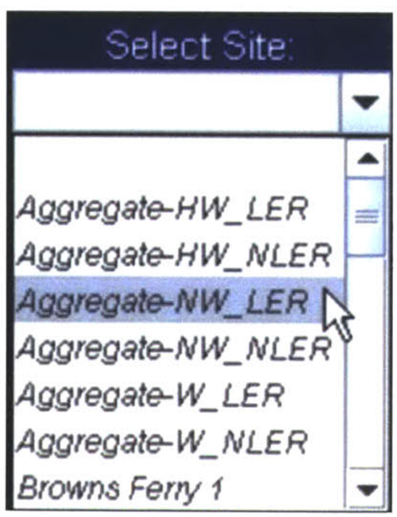


Figure 39. Site selector

Different versions of aggregate network were provided for two reasons: 1) the networks with aggregate weights for links or nodes are overly cluttered. 2) Although HERA was selected as the main resource for identifying the interactions between the sources of complexity, based on its high quality of information, other incident report databases such as Licensee Event Report (LER) may provide more evidence for the existence of identified sources. Although the non-HERA evidences cannot be used to create CSNs, this information can be added to the aggregate network for analysis.

The 6 aggregate networks were categorized by weights (weights for both nodes and links, weights for only nodes, and no weights), and by whether the network includes the data from LER database or not. See Table 12 for the aggregate network terminology.

1. The aggregate network without weights, including the LER data (coded as no-weight or "Aggregate-NW_LER", Figure 40).
2. The aggregate network without weights, but including the LER data (coded as no-weight or "Aggregate-NW_NLER").
3. The aggregate network visualizing the aggregate node weights but not link weights, including the LER data (coded as half-weight or "Aggregate-HW_LER", Figure 41).
4. The aggregate network visualizing the aggregate node weights but not link weights, not including the LER data (coded as half-weight or "Aggregate-HW_NLER").
5. The aggregate network visualizing both weights for nodes and weights for links, including the LER data (coded as full-weight or "Aggregate-W_LER", Figure 42).
6. The aggregate network visualizing both weights for nodes and weights for links, not including the LER data (coded as full-weight or "Aggregate-W_NLER").

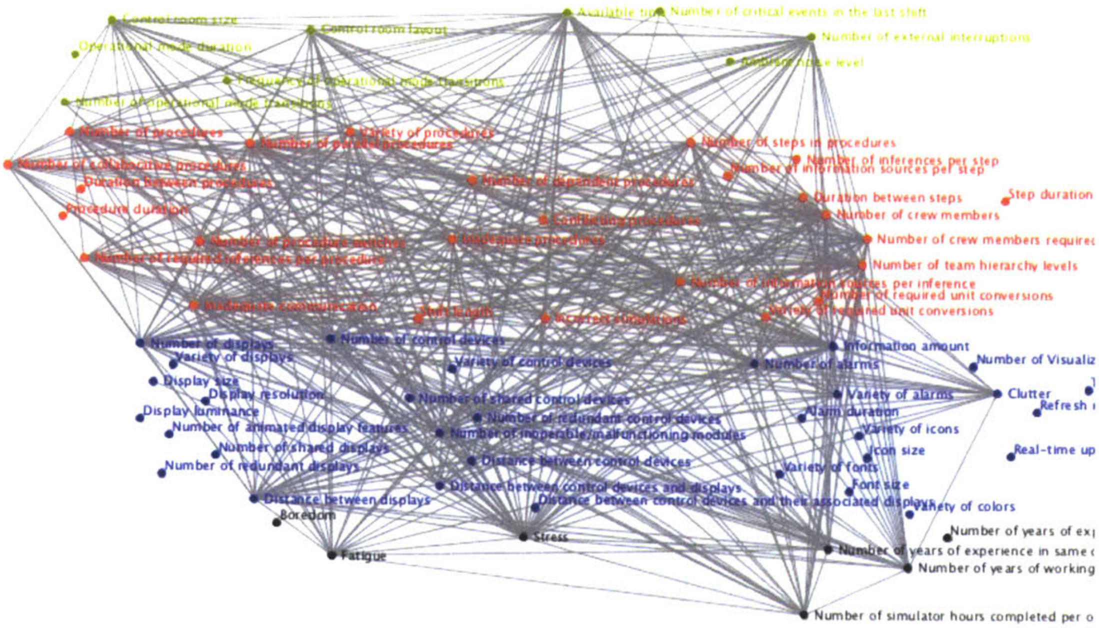


Figure 40. Aggregate no-weight network with LER data

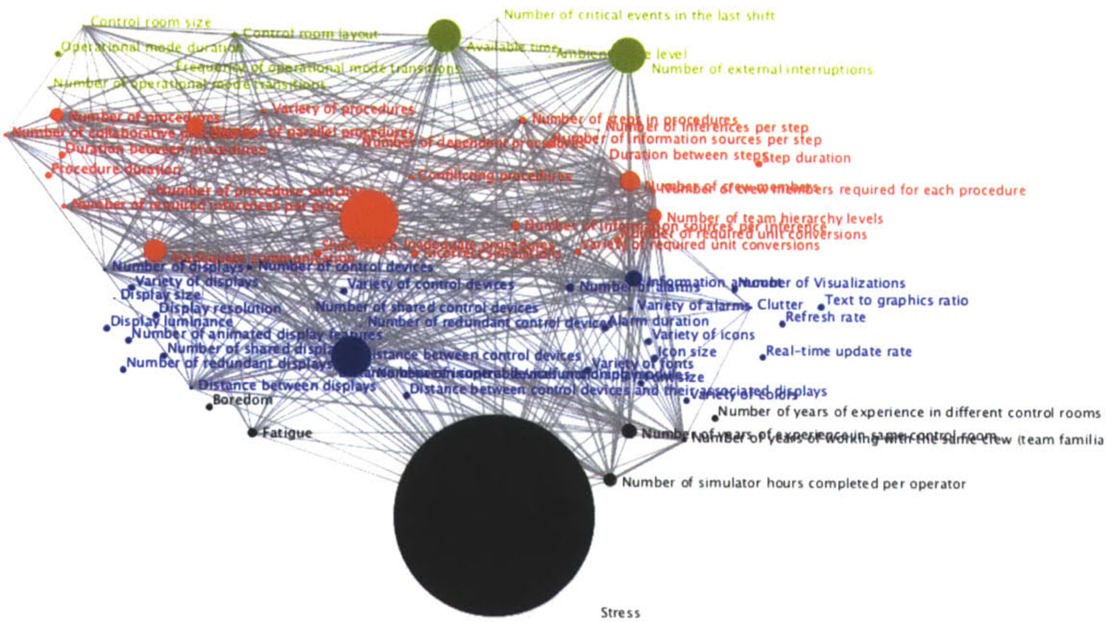


Figure 41. Aggregate half-weight network with LER data.

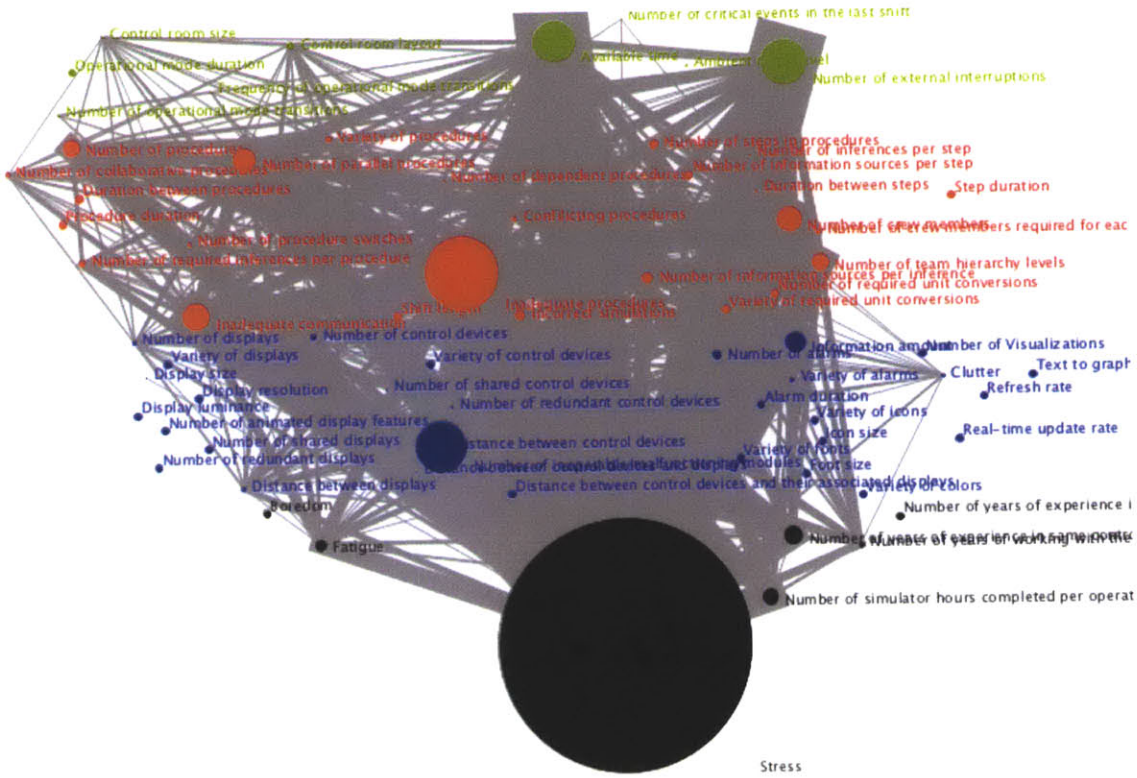


Figure 42. Aggregate full-weight network with LER data

Table 12. Aggregate network terminology.

		LER data included	LER data not included
Weight	**No Weights**	**Aggregate-NW_LER**	**Aggregate-NW_NLER**
	Half Weights	**Aggregate-HW_LER**	**Aggregate-HW_NLER**
	Full Weights	**Aggregate-W_LER**	**Aggregate-W_NLER**

Statistics

The statistics table provides important network characteristics information about the currently loaded network (Figure 43). The statistics are calculated based on the nodes and links on the screen; whenever these are either removed or added the statistics update to reflect the change. As previously discussed in Section 4.6, these network characteristics measure connectivity of a network, which in turn could be used as a direct measure of complexity. Table 13 summarizes these statistics.

Statistics

Stat	Value
Connected Nodes	44
Orphan Nodes	28
Total Links	417
Avg Node Degree	18.955
CPL	2.058
Clustering Coefficient	0.825
CPL with Orphans	0.762

Figure 43. Statistics section

Table 13. Network characteristics information

Characteristic	Definitions
Connected Nodes	Number of nodes with a link to other nodes
Orphan Nodes	Number of nodes with no link to other nodes
Total Links	Total number of links
Average Node Degree	The average number of links connected to nodes
Characteristic Path Length (CPL)	Average distance between pairs of nodes
Clustering Coefficient	The probability that two neighbor nodes for each node are connected
CPL with Orphans	Characteristic Path Length considering the orphan nodes
Degree Distribution (Under Development)	The probability distribution of the node degrees over the whole network

View Options

The “View Options” box contains options that the lets the user to change the level of detail shown on the visualization window. The color-coded “Complexity Levels” refer to the different types of complexity sources in the complexity chain previously discussed in section 4.5, and disabling/enabling the checkboxes hide/reveal the sources and their links respectively (Figure 44).

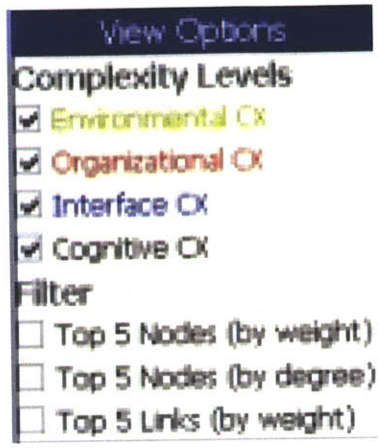


Figure 44. View options

The Complexity levels view option could be used in three ways: 1) Investigating different levels of complexity in isolation, 2) Investigating the interactions between different levels of complexity, and 3) Investigating the effects of removing different levels of complexity on the network characteristics (Figure 45).

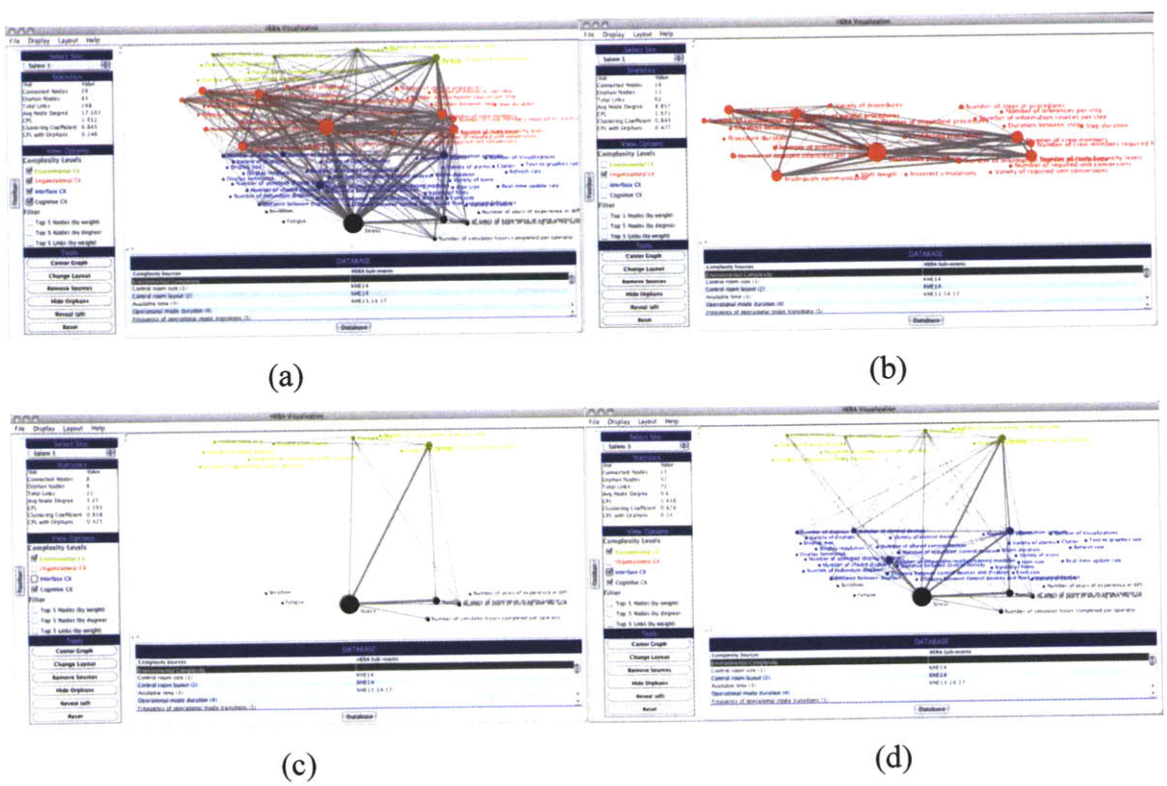


Figure 45. a) Original CSN for the Salem unit 1 incident, b) and the organizational complexity level of Salem 1 incident, c) the connections between the environmental and cognitive complexity levels, and d) Salem 1 CSN without the organizational complexity level.

The "Filter" options give the user three ways to highlight important characteristics of the visible network. Checking one (or more) of the boxes highlights the relevant sources or links while graying out the rest of the network. Each filter option is described briefly in Table 14. Figure 46 shows the situation in which all three filters were used for the "Browns Ferry 1" incident.

Table 14. View filter options

View Filter	Definition
Top 5 Nodes (by weight)	Highlights (in YELLOW) the top 5 sources according to the number of HERA events found for each source
Top 5 Nodes (by degree)	Highlights (in RED) the top 5 sources according to the number of links each source has to other sources
Top 5 Links (by weight)	Highlights (in BLACK) the top 5 links according to the number of HERA events shared by the linked sources
Note: Sources that fall within the three top 5 filters are highlighted in ORANGE.	

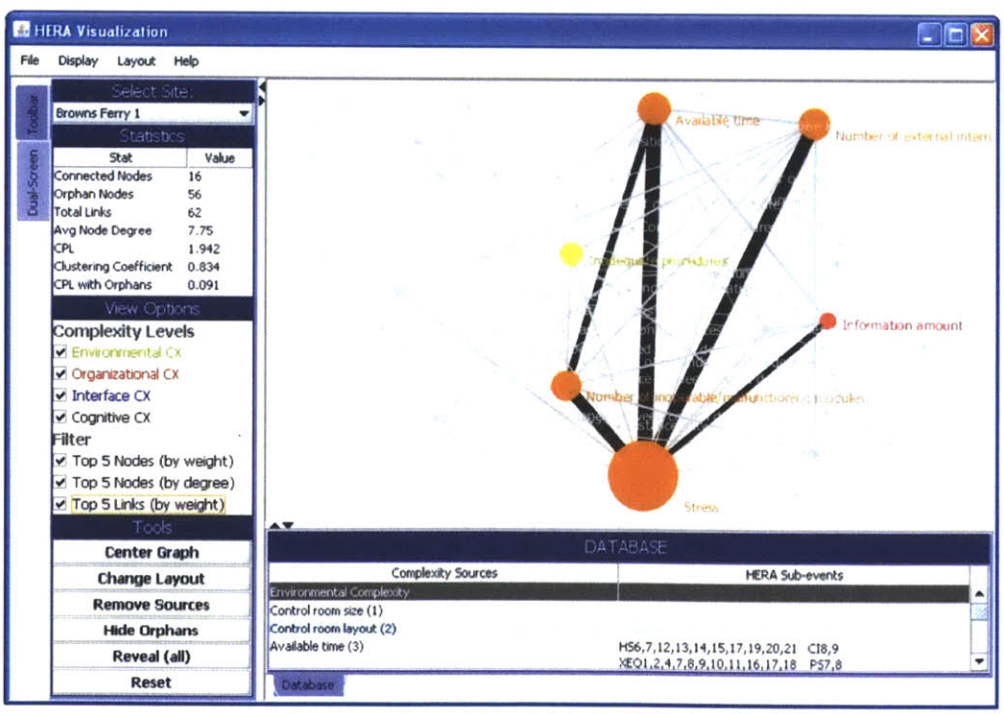


Figure 46. Using filter view options

Tools

The function buttons in the "Tools" box control the graphical window and allow the user to manipulate the chosen network (Figure 47).

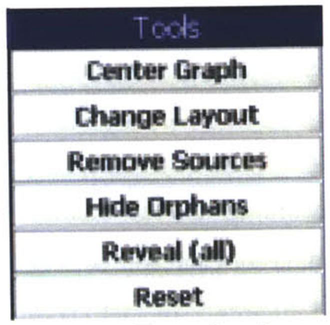


Figure 47. Function buttons

- **Center Graph**: Shows the whole network in the visualization window.
- **Change Layout**: brings up a dialog box asking the user to choose a new layout (Figure 48). Similar to the layout option in the menu bar, the user can choose an algorithm to impose on the currently loaded network (see Table 12). The user may choose from the same choices listen under the "Layout" menu item, as well as "Original", which brings up the original network embodied in the complexity chain.

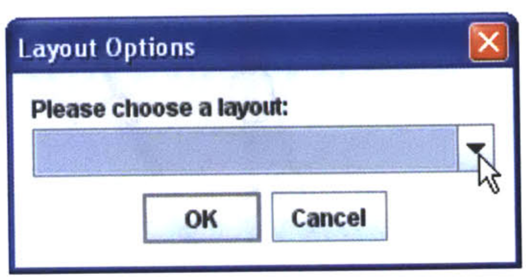


Figure 48. Layout options window

- **Remove Sources**: brings up a dialog box asking the user for the criteria that should be used to remove nodes (Figure 49).

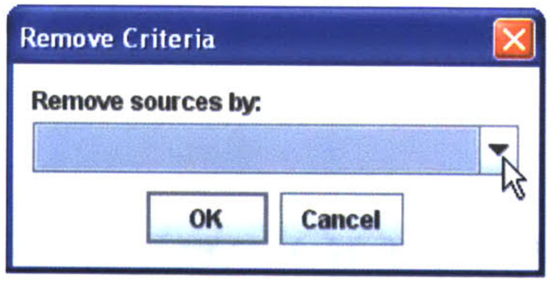


Figure 49. Remove source window

Currently, the user can choose to remove nodes based on their weight (size), or by the number of links they have. Once a choice is made, the user can input the desired minimum. For node weight, this dialog box looks like Figure 50.

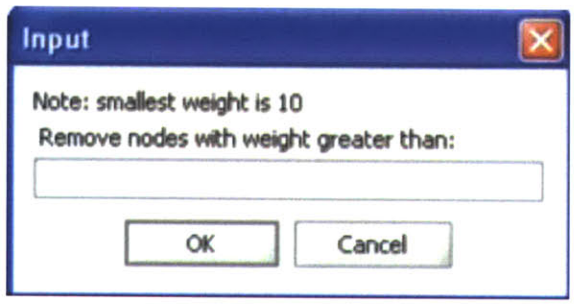


Figure 50. Filter by node weight

The dialogue box for node link number is similar to the node weight dialogue box.

- **Hide Orphans**: hides the nodes that are not connected by links
- **Reveal (all)**: restores all hidden and/or removed elements to their last positions
- **Reset**: restores the network to its original state

F.4: The Database Window

This window appears at the bottom of the applet and displays the data from which the nodes and links are made (Figure 51). In the first column are the identified sources of complexity, grouped according to complexity types (i.e. environmental, organizational, interface and cognitive). In the second column are the HERA incident sub-events that have been identified to support the complexity source for the currently loaded site. The weight (size) of a node in the graphical window corresponds to the number of sub-events that have been identified for that particular complexity source. The weight (width) of a link corresponds to the number of sub-events shared by the two sources it connects.

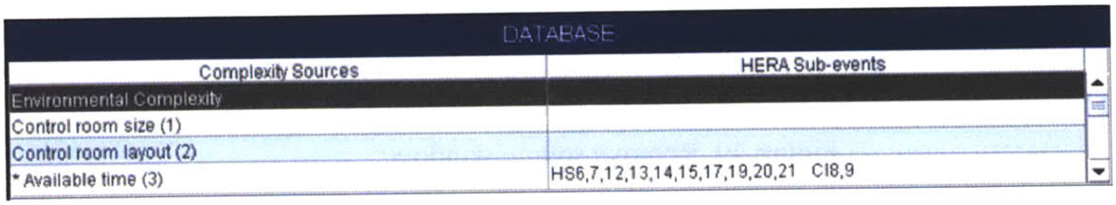


Figure 51. The database window

Clicking a row in the table will select the corresponding node in the graphical window, which will then zoom and center on it. Likewise, clicking a node on the graph causes the view to zoom and center on it, and causes the data table to scroll to the corresponding row of data and highlight it. Currently, the data table is not editable, but may in the future allow the user to add sub-events and complexity sources to the database.

F.5: Side-by-side network displays

A feature that is currently in development is the ability to display two networks in a split screen mode. Two drop down menus will allow the user to select the networks to display. These menus will be on a second tab on the left-hand side of the screen. The statistics for both networks will also appear in this panel in a setup similar to what is currently used for a single network. This feature will allow the user to compare two networks more easily than the program currently allows.

Appendix G: Network Statistics for 22 Incidents in HERA

HERA Incident	Connected Nodes	Orphan Nodes	Total Links	Avg Node Degree	CPL	CPL with Orphans	CC
WC	15	57	51	6.8	2.371	0.856	0.097
W3	10	62	30	6.0	1.6	0.948	0.028
TMI	22	50	97	8.818	1.896	0.826	0.171
S1	29	43	248	17.103	1.574	0.845	0.25
QC2	0	72	0	0	0	0	0
PB1	2	70	1	1.0	1.0	0	0.0
PB2	11	61	21	3.818	1.764	0.789	0.038
PV1/2	18	54	62	6.889	1.954	0.842	0.117
PV1/1	9	63	14	3.111	2.0	0.758	0.028
NA1	30	42	217	14.467	1.736	0.833	0.295
LS2	7	65	10	2.857	1.762	0.878	0.014
IP3	2	70	1	1.0	1.0	0	0.0
IP2/2	3	69	2	1.333	1.333	0.0	0.0020
IP2/1	14	58	29	4.143	2.0	0.806	0.071
G	5	67	5	2.0	1.5	0.722	0.0060
FP	3	69	2	1.333	1.333	0.0	0.0020
F2	4	68	2	1.0	1.0	0	0.0010
DC1	8	64	12	3.0	1.929	0.739	0.021
DB	4	68	5	2.5	1.333	0.833	0.0030
CP2	2	70	1	1.0	1.0	0	0.0
CR3	13	59	54	8.308	1.603	0.873	0.049
CC1	11	61	39	7.091	1.927	0.889	0.041
BF1	16	56	62	7.75	1.942	0.834	0.091

Where, **CPL**: Characteristic path length and **CC**: Clustering coefficient

Appendix H: CXSurvey Consent Form

CONSENT TO PARTICIPATE IN

NON-BIOMEDICAL RESEARCH

Automation and HSI Complexity in Advanced Reactors

You are asked to participate in a research study conducted by Farzan Sasangohar (student investigator) and Professor Mary Cummings PhD, (Principal Investigator) from the Massachusetts Institute of Technology (M.I.T.). Please read the information below, and ask questions about anything you do not understand, and then decide whether or not to participate.

PARTICIPATION AND WITHDRAWAL

Your participation in this study is completely voluntary; you may withdraw from it at any time without consequences of any kind.

PURPOSE OF THE STUDY

The overall objective of this study is to develop a better understanding of how humans perceive complexity in the NPP control room environment. The goals of this study are to evaluate the proposed sources of complexity within NPP control rooms and to, generally, further our understanding of complexity to inform guidelines for evaluating NPP control rooms.

PROCEDURES

If you volunteer to participate in this study, we would ask you to do complete the following steps:

- Complete an informed consent form.
- Answer a series of questions about complexity on an apple iPad.

The total time for this interview is approximately 30 minutes.

POTENTIAL BENEFITS

Your efforts will provide critical insight into the human perceived complexity of control rooms and will help the research team to develop complexity guidelines to inform the review of control room designs.

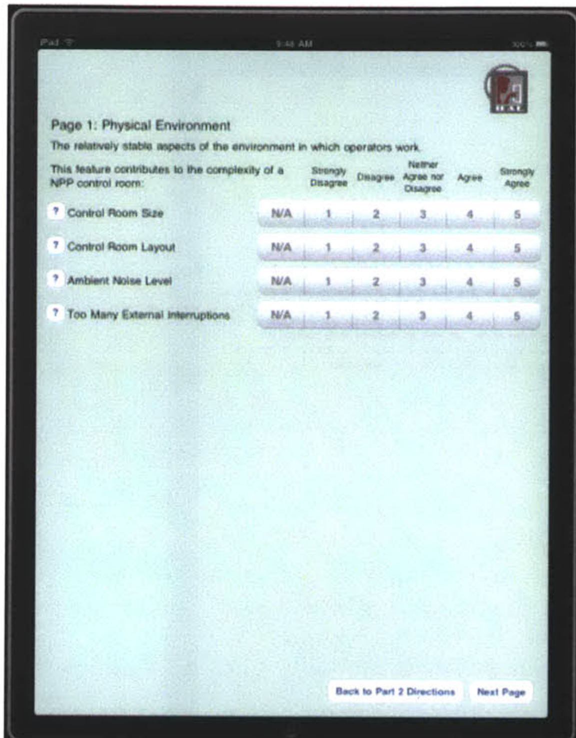
CONFIDENTIALITY

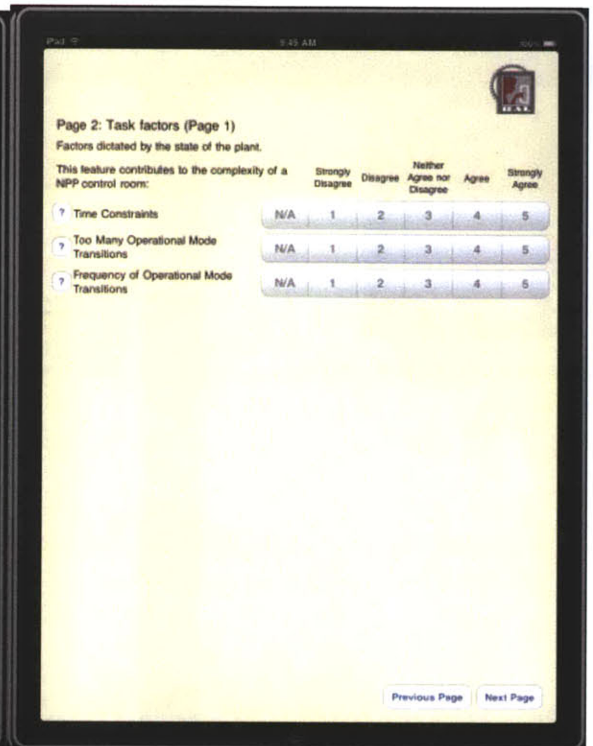
This study is anonymous. You will be assigned a subject number, which will be used in all data files to guarantee anonymity. We do not keep any information that is obtained in connection with this study and that can be identified with you.

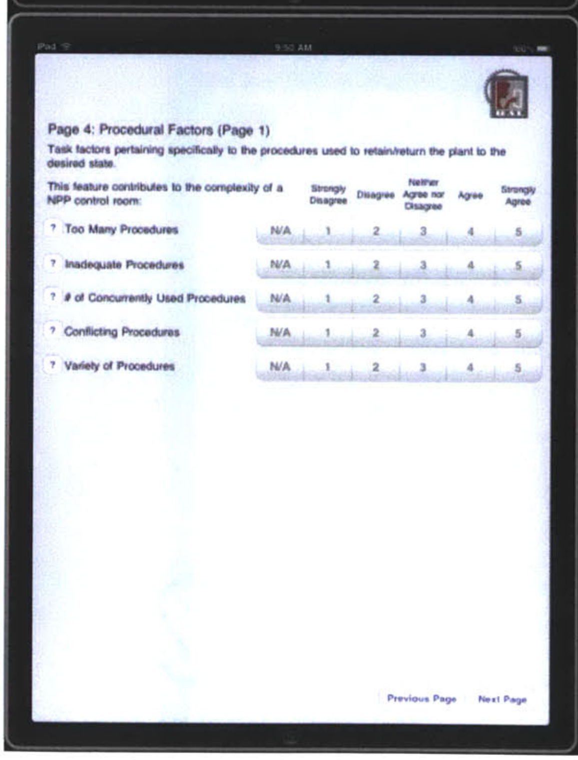
IDENTIFICATION OF INVESTIGATORS

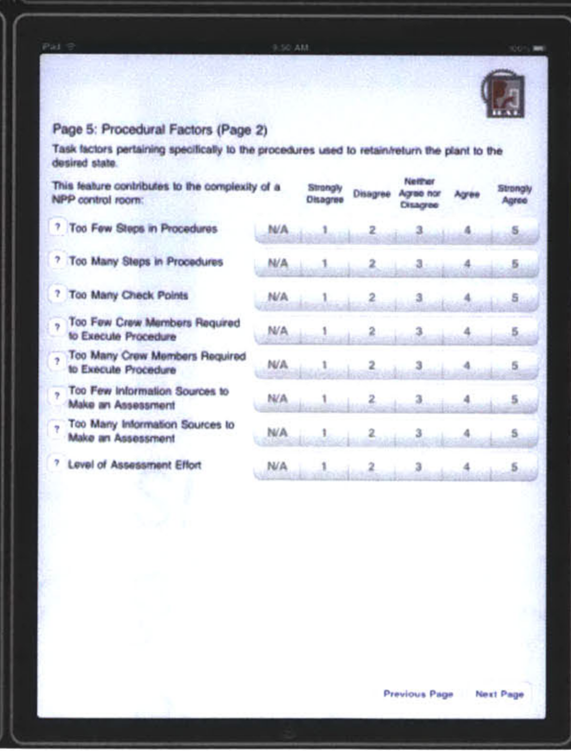
If you have any questions or concerns about the research, please feel free to contact the Principal Investigator, Mary L. Cummings, at (617) 252-1512, e-mail, missyc@mit.edu, and her address is 77 Massachusetts Avenue, Room 33-305, Cambridge, MA, 02139. The student investigator is Farzan Sasangohar and he may be contacted by telephone at (617) 768-7771 or via email at farzans@mit.edu.

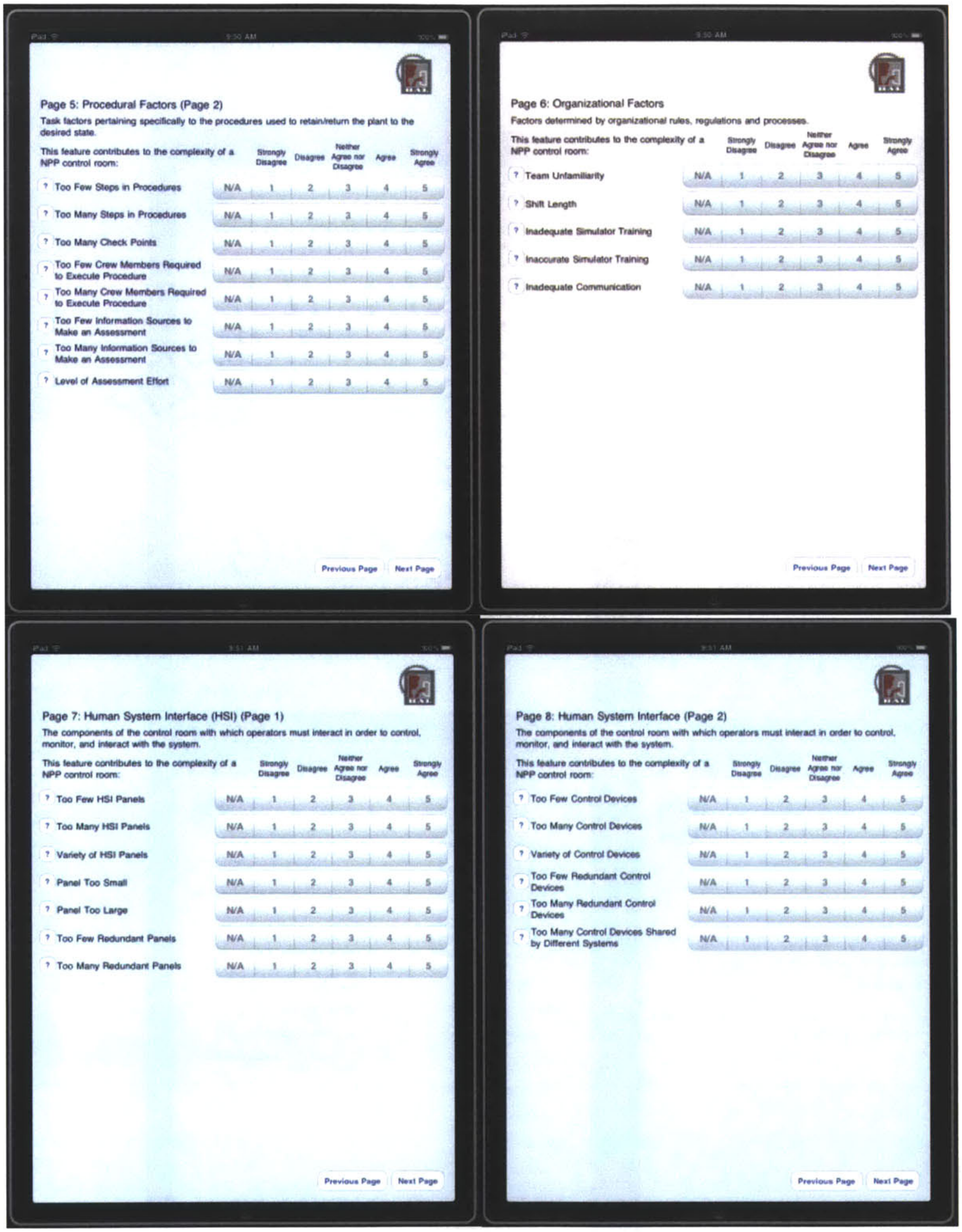
Appendix I: CXSurvey Screenshots

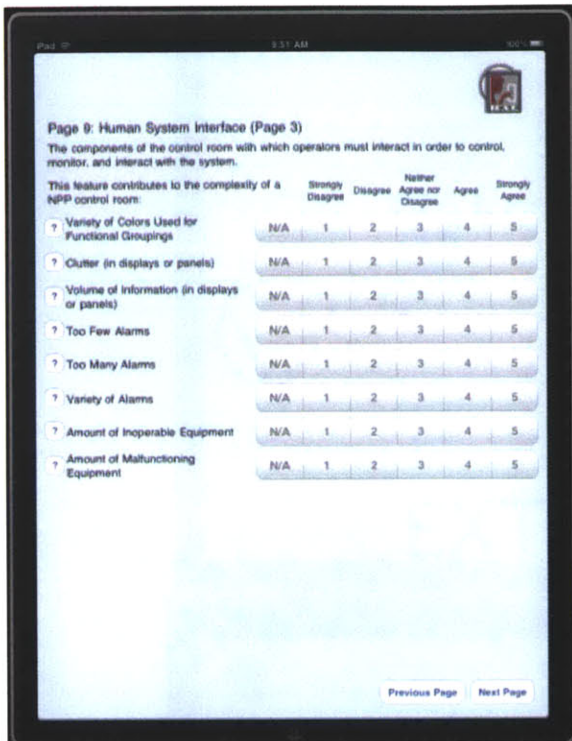

Page 1: Physical Environment
The relatively stable aspects of the environment in which operators work.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Control Room Size
Control Room Layout
Ambient Noise Level
Too Many External Interruptions
N/A 1 2 3 4 5
Back to Part 2 Directions
Next Page


Page 2: Task factors (Page 1)
Factors dictated by the state of the plant.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Time Constraints
Too Many Operational Mode Transitions
Frequency of Operational Mode Transitions
N/A 1 2 3 4 5
Previous Page
Next Page

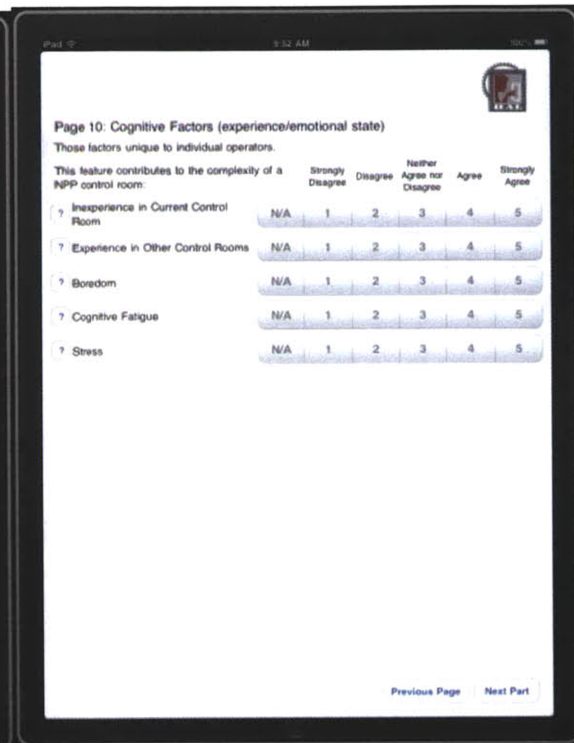

Page 4: Procedural Factors (Page 1)
Task factors pertaining specifically to the procedures used to retain/return the plant to the desired state.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Too Many Procedures
Inadequate Procedures
# of Concurrently Used Procedures
Conflicting Procedures
Variety of Procedures
N/A 1 2 3 4 5
Previous Page
Next Page


Page 5: Procedural Factors (Page 2)
Task factors pertaining specifically to the procedures used to retain/return the plant to the desired state.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Too Few Steps in Procedures
Too Many Steps in Procedures
Too Many Check Points
Too Few Crew Members Required to Execute Procedure
Too Many Crew Members Required to Execute Procedure
Too Few Information Sources to Make an Assessment
Too Many Information Sources to Make an Assessment
Level of Assessment Effort
N/A 1 2 3 4 5
Previous Page
Next Page

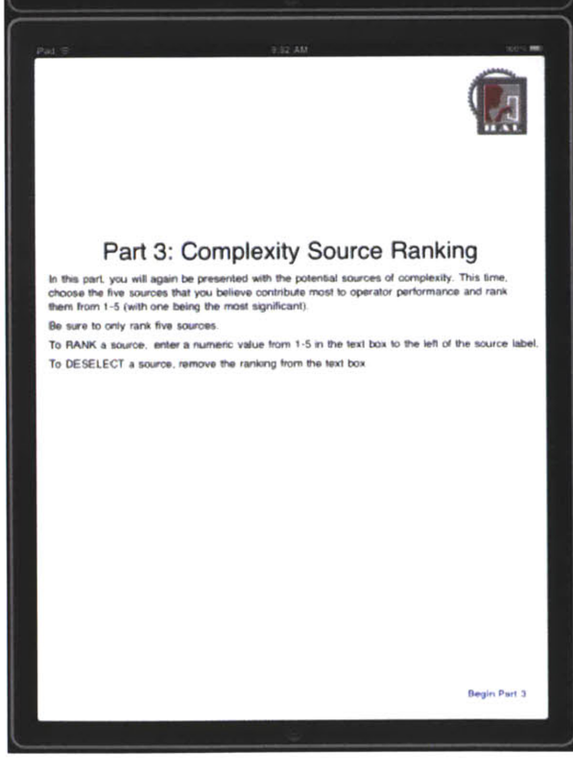

Page 5: Procedural Factors (Page 2)
Task factors pertaining specifically to the procedures used to retain/return the plant to the desired state.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Too Few Steps in Procedures
Too Many Steps in Procedures
Too Many Check Points
Too Few Crew Members Required to Execute Procedure
Too Many Crew Members Required to Execute Procedure
Too Few Information Sources to Make an Assessment
Too Many Information Sources to Make an Assessment
Level of Assessment Effort
N/A 1 2 3 4 5
Previous Page
Next Page
Page 6: Organizational Factors
Factors determined by organizational rules, regulations and processes.
This feature contributes to the complexity of a NPP control room:
Team Unfamiliarity
Shift Length
Inadequate Simulator Training
Inaccurate Simulator Training
Inadequate Communication
Page 7: Human System Interface (HSI) (Page 1)
The components of the control room with which operators must interact in order to control, monitor, and interact with the system.
This feature contributes to the complexity of a NPP control room:
Too Few HSI Panels
Too Many HSI Panels
Variety of HSI Panels
Panel Too Small
Panel Too Large
Too Few Redundant Panels
Too Many Redundant Panels
Page 8: Human System Interface (Page 2)
The components of the control room with which operators must interact in order to control, monitor, and interact with the system.
This feature contributes to the complexity of a NPP control room:
Too Few Control Devices
Too Many Control Devices
Variety of Control Devices
Too Few Redundant Control Devices
Too Many Redundant Control Devices
Too Many Control Devices Shared by Different Systems



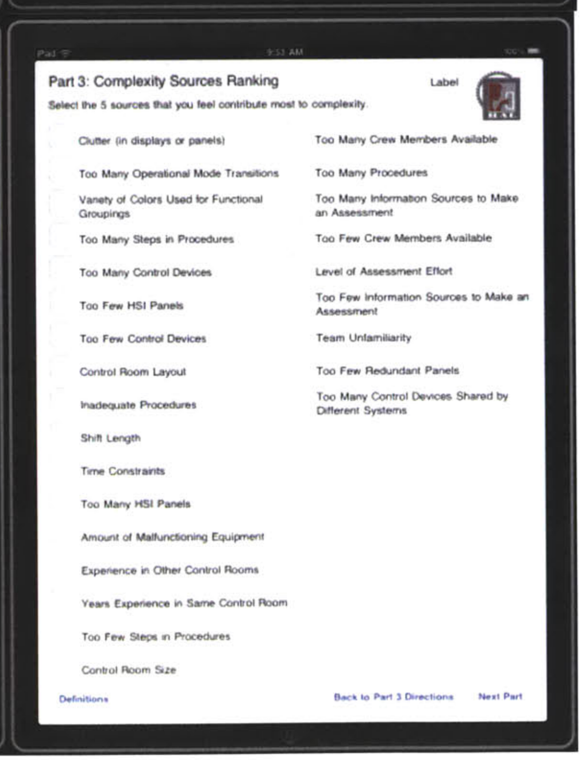
Page 9: Human System Interface (Page 3)
The components of the control room with which operators must interact in order to control, monitor, and interact with the system.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Variety of Colors Used for Functional Groupings
Clutter (in displays or panels)
Volume of Information (in displays or panels)
Too Few Alarms
Too Many Alarms
Variety of Alarms
Amount of Inoperable Equipment
Amount of Malfunctioning Equipment
N/A 1 2 3 4 5
Previous Page
Next Page



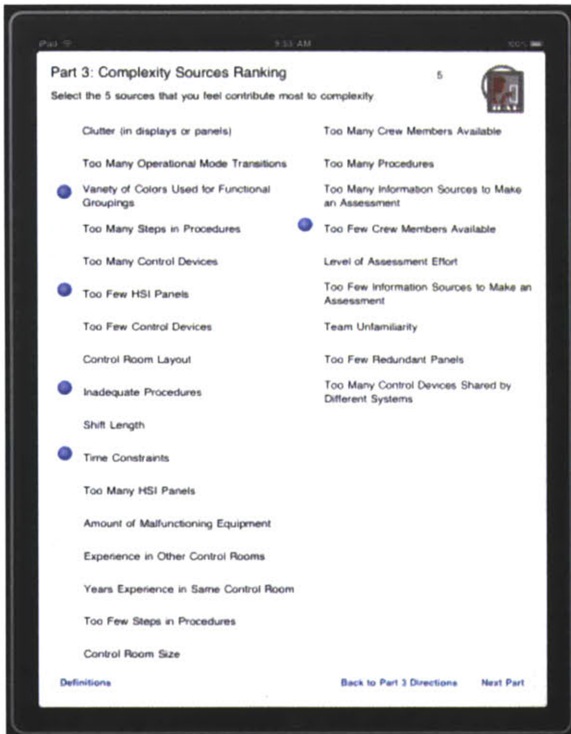
Page 10: Cognitive Factors (experience/emotional state)
Those factors unique to individual operators.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Inexperience in Current Control Room
Experience in Other Control Rooms
Boredom
Cognitive Fatigue
Stress
N/A 1 2 3 4 5
Previous Page
Next Part

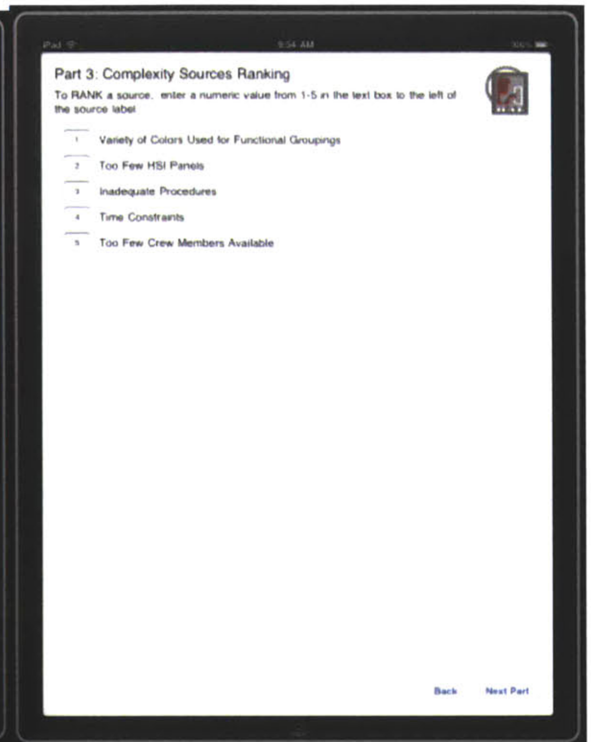


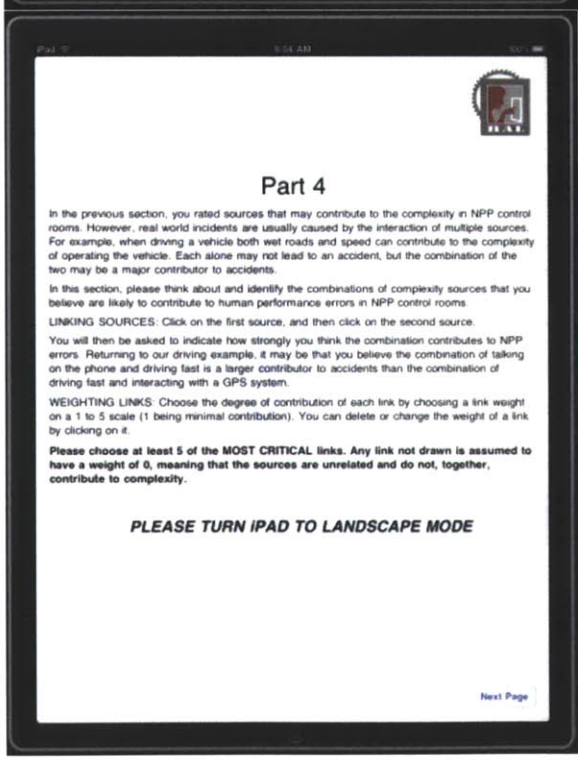
Part 3: Complexity Source Ranking
In this part, you will again be presented with the potential sources of complexity. This time, choose the five sources that you believe contribute most to operator performance and rank them from 1-5 (with one being the most significant).
Be sure to only rank five sources.
To RANK a source, enter a numeric value from 1-5 in the text box to the left of the source label.
To DESELECT a source, remove the ranking from the text box.
Begin Part 3



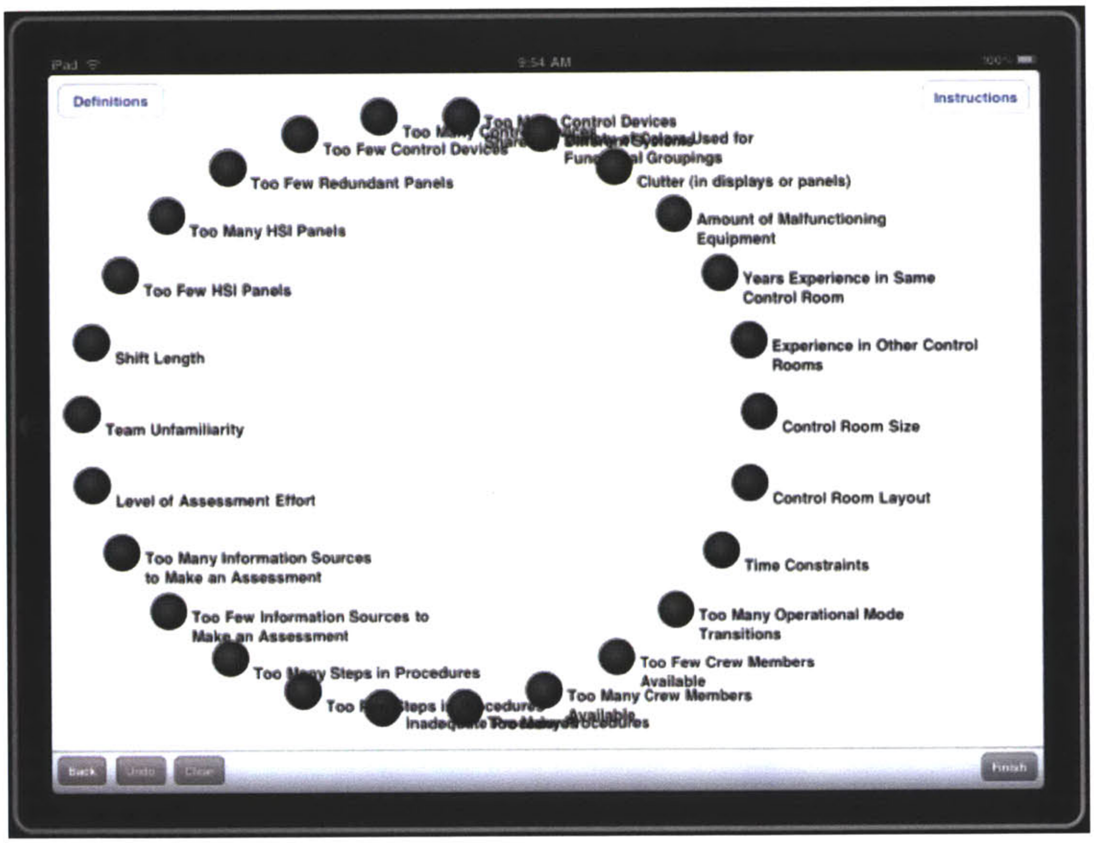
Part 3: Complexity Sources Ranking
Label
Select the 5 sources that you feel contribute most to complexity.
Clutter (in displays or panels)
Too Many Operational Mode Transitions
Variety of Colors Used for Functional Groupings
Too Many Steps in Procedures
Too Many Control Devices
Too Few HSI Panels
Too Few Control Devices
Control Room Layout
Inadequate Procedures
Shift Length
Time Constraints
Too Many HSI Panels
Amount of Malfunctioning Equipment
Experience in Other Control Rooms
Years Experience in Same Control Room
Too Few Steps in Procedures
Control Room Size
Too Many Crew Members Available
Too Many Procedures
Too Many Information Sources to Make an Assessment
Too Few Crew Members Available
Level of Assessment Effort
Too Few Information Sources to Make an Assessment
Team Unfamiliarity
Too Few Redundant Panels
Too Many Control Devices Shared by Different Systems
Definitions
Back to Part 3 Directions
Next Part


Part 3: Complexity Sources Ranking
5
Select the 5 sources that you feel contribute most to complexity
Clutter (in displays or panels)
Too Many Operational Mode Transitions
Variety of Colors Used for Functional Groupings
Too Many Steps in Procedures
Too Many Control Devices
Too Few HSI Panels
Too Few Control Devices
Control Room Layout
Inadequate Procedures
Shift Length
Time Constraints
Too Many HSI Panels
Amount of Malfunctioning Equipment
Experience in Other Control Rooms
Years Experience in Same Control Room
Too Few Steps in Procedures
Control Room Size
Too Many Crew Members Available
Too Many Procedures
Too Many Information Sources to Make an Assessment
Too Few Crew Members Available
Level of Assessment Effort
Too Few Information Sources to Make an Assessment
Team Unfamiliarity
Too Few Redundant Panels
Too Many Control Devices Shared by Different Systems
Definitions
Back to Part 3 Directions
Next Part

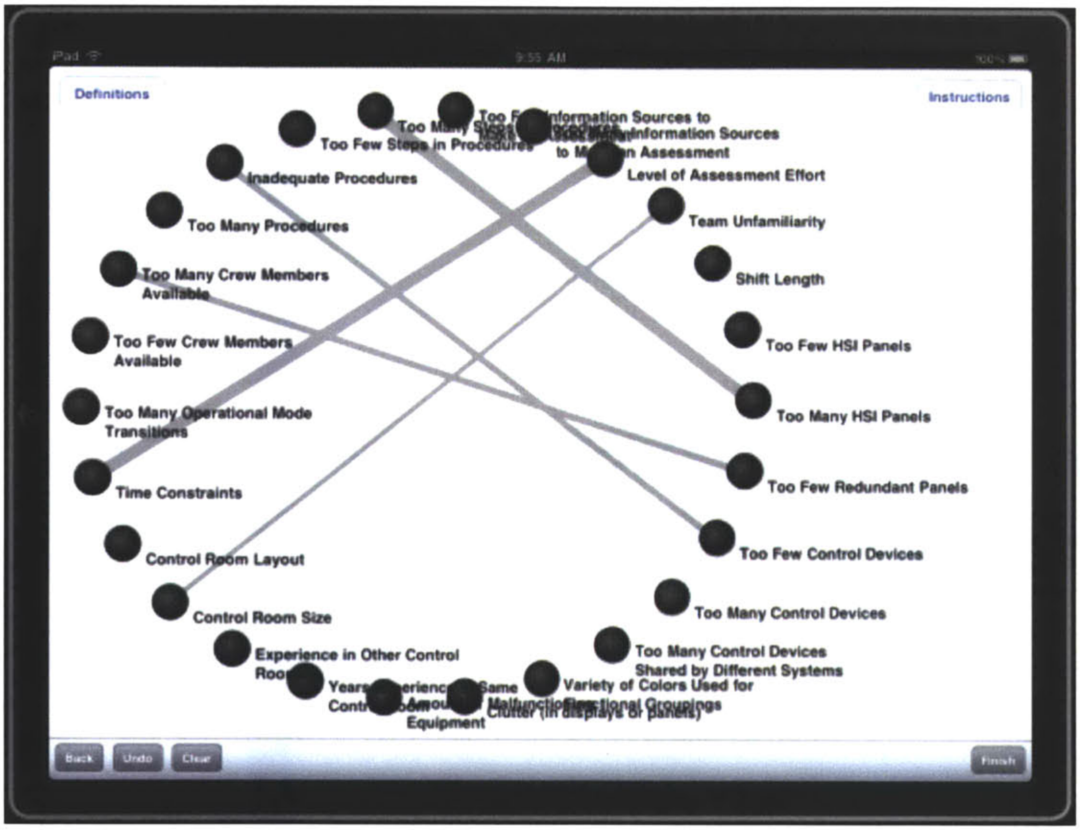

Part 3: Complexity Sources Ranking
To RANK a source, enter a numeric value from 1-5 in the text box to the left of the source label
1 Variety of Colors Used for Functional Groupings
2 Too Few HSI Panels
3 Inadequate Procedures
4 Time Constraints
5 Too Few Crew Members Available
Back
Next Part

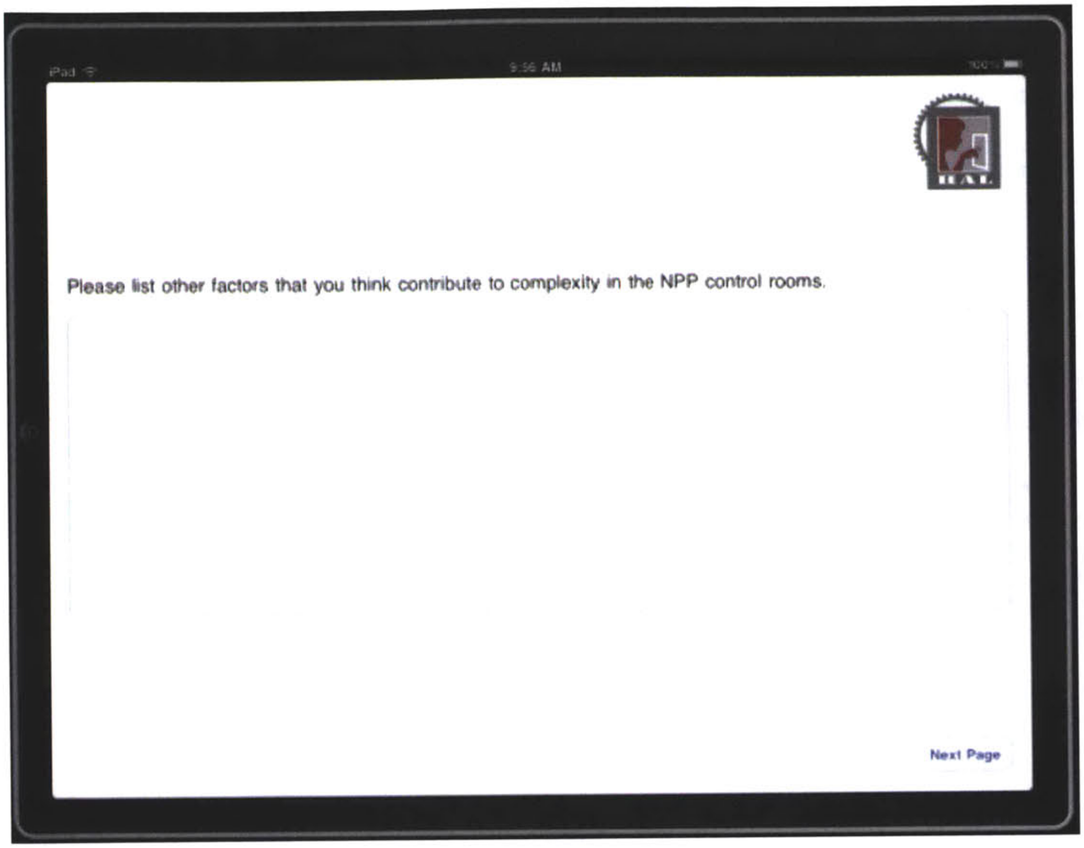

Part 4
In the previous section, you rated sources that may contribute to the complexity in NPP control rooms. However, real world incidents are usually caused by the interaction of multiple sources. For example, when driving a vehicle both wet roads and speed can contribute to the complexity of operating the vehicle. Each alone may not lead to an accident, but the combination of the two may be a major contributor to accidents.
In this section, please think about and identify the combinations of complexity sources that you believe are likely to contribute to human performance errors in NPP control rooms.
LINKING SOURCES: Click on the first source, and then click on the second source.
You will then be asked to indicate how strongly you think the combination contributes to NPP errors. Returning to our driving example, it may be that you believe the combination of talking on the phone and driving fast is a larger contributor to accidents than the combination of driving fast and interacting with a GPS system.
WEIGHTING LINKS: Choose the degree of contribution of each link by choosing a link weight on a 1 to 5 scale (1 being minimal contribution). You can delete or change the weight of a link by clicking on it.
Please choose at least 5 of the MOST CRITICAL links. Any link not drawn is assumed to have a weight of 0, meaning that the sources are unrelated and do not, together, contribute to complexity.
PLEASE TURN iPAD TO LANDSCAPE MODE
Next Page

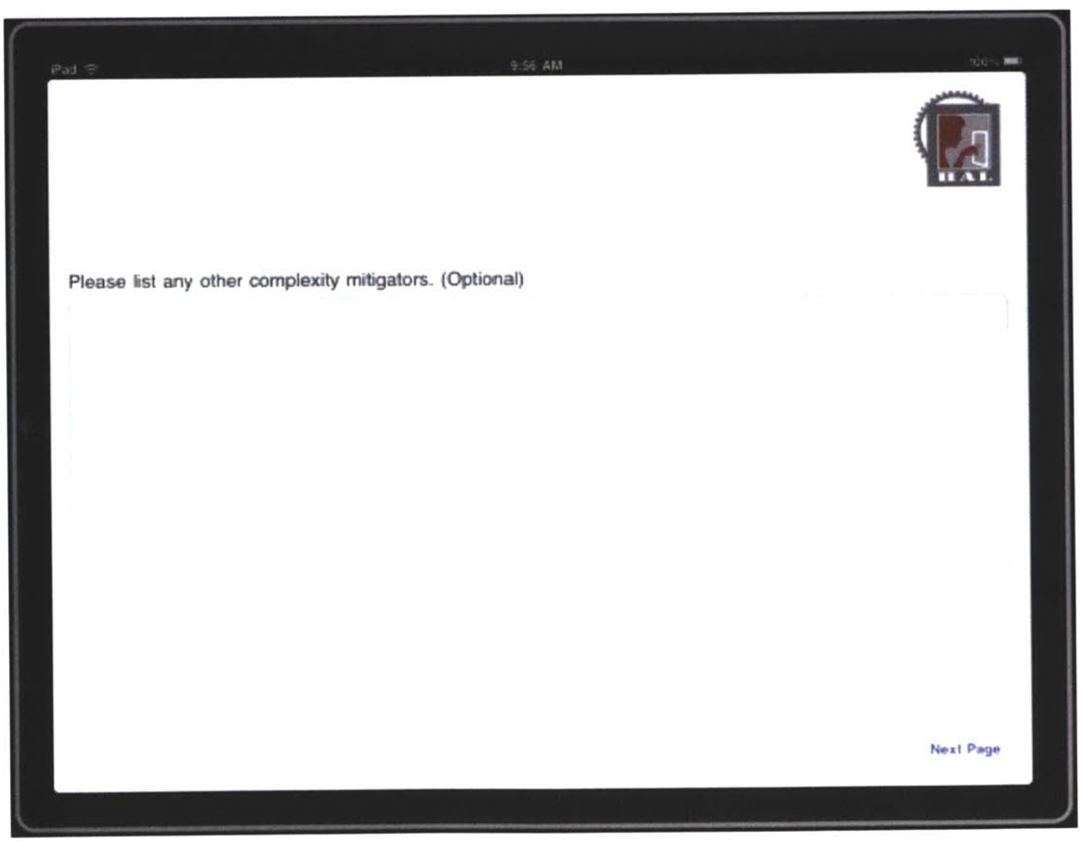
In this page interviewees view a CSN based on the rating they provide in the previous section. IN order to mitigate clutter only the sources that were rated as either 4 (agree) or 5 (strongly agree) were shown here. The interviewees were asked to identify potential interactions between the sources by drawing a link between pairs of nodes.

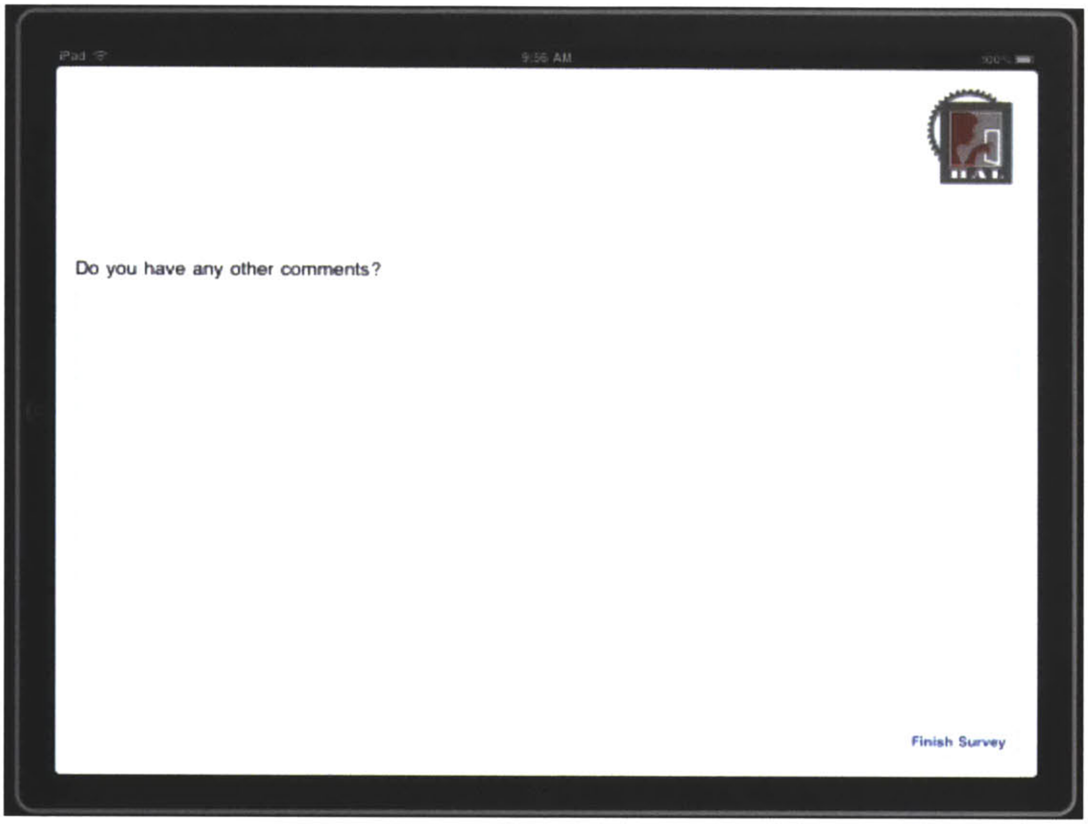


For example in this interface the interviewee has identified 5 links between the sources. Also as shown in the figure, the interviewee can choose a link weight on a 5-point Likert scale (1 being the least important, 5 being the most important) to imply the importance of a link.




iPad
9:56 AM
100%
Please list other factors that you think contribute to complexity in the NPP control rooms.
Next Page


iPad
9:56 AM
100%
Please list any other complexity mitigators. (Optional)
Next Page



iPad
9:56 AM
Do you have any other comments?
Finish Survey

Appendix J: Top 5 selections of different groups

Table 15.Top 5 selections for 8 Designers (D1-8)

D1	D2
1. # of Concurrently Used Procedures	1. Too Many Information Sources to Make an Assessment
2. Too Many Redundant Control Devices	2. Level of Assessment Effort
3. Level of Assessment Effort	3. Too Many Procedures
4. Amount of Inoperable Equipment	4. # of Concurrently Used Procedures
5. Cognitive Fatigue	5. Inadequate Procedures
D3	D4
1. Time Constraints	1. Inadequate Communication
2. Too Many Information Sources to Make an Assessment	2. Too Many External Interruptions
3. Too Many Procedures	3. Inadequate Simulator Training
4. Ambient Noise Level	4. Too Many Alarms
5. Too Many Alarms	5. Inadequate Procedures

D5	D6
1. Too Many Alarms	1. Inaccurate Simulator Training
2. Volume of Information (in displays or panels)	2. Too Many Information Sources to Make an Assessment
3. Too Many Control Devices Shared by Different Systems	3. Too Many Alarms
4. Inaccurate Simulator Training	4. Inadequate Simulator Training
5. Amount of Malfunctioning Equipment	5. Variety of Colors Used for Functional Groupings
D7	**D8**
1. Control Room Layout	1. Too Few Information Sources to Make an Assessment
2. Volume of Information (in displays or panels)	2. # of Concurrently Used Procedures
3. Variety of Control Devices	3. Too Many Operational Mode Transitions
4. Time Constraints	4. Amount of Malfunctioning Equipment
5. Clutter (in displays or panels)	5. Inadequate Procedures

Table 16. Top 5 selections for 3 Operators (O1-3).

O1	O2
1. Amount of Malfunctioning Equipment	1. Inadequate Communication
2. Too Many External Interruptions	2. Too Many Alarms
3. Volume of Information (in displays or panels)	3. Too Many External Interruptions
4. Too Many Alarms	4. Shift Length
5. Control Room Layout	5. Volume of Information (in displays or panels)
O3	
1. Volume of Information (in displays or panels)	
2. Amount of Malfunctioning Equipment	
3. Too Many Alarms	
4. # of Concurrently Used Procedures	
5. Too Many External Interruptions	

Table 17. Top 5 selections for 3 Reviewers (R1-3).

R1	R2
1. Too Many External Interruptions	1. Control Room Layout
2. Amount of Inoperable Equipment	2. Years Experience in Same Control Room
3. Time Constraints	3. Stress
4. # of Concurrently Used Procedures	4. Time Constraints
5. Stress	5. Cognitive Fatigue
R3	
1. Inadequate Procedures	
2. Inadequate Simulator Training	
3. Cognitive Fatigue	
4. Time Constraints	
5. Inadequate Communication	

Table 18. Top 5 selections for 6 researchers.

Re1	Re2
1. Volume of Information (in displays or panels)	1. Inadequate Procedures
2. Amount of Malfunctioning Equipment	2. Too Many Alarms
3. Too Many Alarms	3. Inadequate Communication
4. # of Concurrently Used Procedures	4. Clutter (in displays or panels)
5. Too Many External Interruptions	5. Variety of HSI Panels
Re3	Re4
1. Inadequate Procedures	1. Conflicting Procedures
2. Too Few Crew Members Available	2. Inadequate Simulator Training
3. Time Constraints	3. Cognitive Fatigue
4. Level of Assessment Effort	4. # of Concurrently Used Procedures
5. Too Few Information Sources to Make an Assessment	5. Inaccurate Simulator Training

Re5	Re6
1. Inadequate Simulator Training	1. Inadequate Simulator Training
2. Too Few Information Sources to Make an Assessment	2. Level of Assessment Effort
3. Inadequate Communication	3. Time Constraints
4. Inadequate Procedures	4. Inadequate Procedures
5. Too Many Alarms	5. Cognitive Fatigue

Appendix K: Stakeholder Groups' Identified Sources

Ranking	Objective	Designers	Operators	Reviewers
1	Stress	Too Many Information Sources to Make an Assessment	Amount of Malfunctioning Equipment	Time Constraints
2	Inadequate procedures	#Concurrently used Procedures	Volume of Information	Too Many External Interruptions
3	Available time	Too Many Alarms	Too Many Alarms	Control Room Layout
4	Number of external interruptions	Volume of Information	Too Many External Interruptions	Inadequate Procedures
5	Number of inoperable modules	Inadequate Simulator Training	Inadequate Communication	Stress
6	Inadequate communication	Level of Assessment Effort	Shift Length	Inaccurate Simulator Training
7	Number of parallel procedures	Time Constraints	# of Concurrently Used Procedures	Amount of Inoperable Equipment
8	Number of crew members	Too Many Procedures		Years Experience in Same Control Room
9	Number of years of experience in same control room	Too Few Information Sources to Make an Assessment		Cognitive Fatigue
10	Information amount	Control Room Layout		# of Concurrently Used Procedures
11	Number of procedures, Number of team hierarchy levels	Inadequate Communication		

Ranking	Objective	Designers	Operators	Reviewers
12	Number of simulator hours completed per operator	Too Many Redundant Control Devices		
13	Number of malfunctioning modules	Too Many External Interruptions		
14	Incorrect simulations, Number of alarms	Variety of Control Devices		
15	Number of steps in procedures	Too Many Operational Mode Transitions		
16	Fatigue, Number of information sources per inference	Too Many Control Devices Shared by Different Systems		
17	Control room layout	Amount of Malfunctioning Equipments		
18	Number of required inferences per procedure	Inadequate Procedures		
19	Conflicting procedures, Number of years of working with the same crew (team familiarity), Variety of procedures	Amount of Inoperable Equipment		
20	Number of control devices, Number of crew members required for each procedure	Ambient Noise Level		
21	Distance between displays, Variety of alarms			

Ranking	Objective	Designers	Operators	Reviewers
22	Number of collaborative procedures, Number of procedure switches			
23	Number of displays			
24	Ambient noise level, Clutter, Number of redundant control devices			
25	Control room size, Number of inferences per step			
26	Duration between steps, Frequency of operational mode transitions, Number of critical events in the last shift, Number of dependent procedures, Number of operational mode transitions, Number of shared control devices			
27	Display size, Distance between control devices, Distance between control devices and displays			

Appendix L: Node-Weight Contribution of Sources

Table 19. Percentage of contribution for environmental complexity sources

Environmental Complexity	Contribution Percentage
Control room size	0.18
Control room layout	0.90
Available time	5.62
Operational mode duration	0
Frequency of operational mode transitions	0.12
Number of operational mode transitions	0.12
Number of critical events in the last shift	0.12
Number of external interruptions	5.20
Ambient noise level	0.24
Sum	**12.48%**

Table 20. Percentage of contribution for cognitive complexity sources

Cognitive Complexity	Contribution Percentage
Number of years of experience in different control rooms	0
Number of years of experience in same control room	2.69
Number of years of working with the same crew (team familiarity)	0.66
Number of simulator hours completed per operator	2.21
Boredom	0
Fatigue	1.02
Stress	35.30
Sum	**41.87%**

Table 21. Percentage of contribution for organizational complexity sources

Organizational Complexity	**Contribution Percentage**
Number of procedures	2.27
Variety of procedures	0.66
Number of dependent procedures	0.12
Number of parallel procedures	3.17
Number of collaborative procedures	0.42
Conflicting procedures	0.66
Inadequate procedures	10.75
Number of procedure switches	0.42
Duration between procedures	0
Duration of procedures	0
Number of required inferences per procedure	0.78
Number of steps in procedures	1.14
Number of inferences per step	0.18
Number of information sources per step	0
Duration between steps	0.12
Duration of steps	0
Number of information sources per inference	1.02
Number of required unit conversions	0
Variety of required unit conversions	0
Number of crew members	2.81
Number of crew members required for each procedure	0.54
Number of team hierarchy levels	2.27
Shift length	0
Incorrect simulations	1.19
Inadequate communication	3.88
Sum	**32.38%**

Table 22. Percentage of contribution for interface complexity sources.

Interface Complexity	Contribution Percentage
Number of displays	0.30
Variety of displays	0
Display size	0.06
Display resolution	0
Display luminance	0
Number of animated display features	0
Number of shared displays	0
Number of redundant displays	0
Distance between displays	0.48
Number of control devices	0.54
Variety of control devices	0
Number of shared control devices	0.12
Number of redundant control devices	0.24
Number of inoperable modules	4.96
Number of malfunctioning modules	2.15
Distance between control devices	0.06
Distance between control devices and displays	0.06
Distance between controls and their associated displays	0
Clutter	0.24
Information amount	2.39
Number of alarms	1.19
Variety of alarms	0.48
Alarm duration	0
Variety of icons	0
Icon size	0
Variety of fonts	0
Font size	0

Variety of colors	0
Number of visualizations	0
Text to graphics ratio	0
Refresh rate	0
Real-time update rate	0
Sum	**13.26%**

Appendix M: Source Rating Descriptive Analysis

	The source contributes to perceived complexity												
	Not Applicable	**%**	**Strongly disagree**	**%**	**Disagree**	**%**	**Undecided**	**%**	**Agree**	**%**	**Strongly agree**	**%**	**Response average**
Control Room Size	1	5	0	0	4	20	**8**	**40**	6	30	1	5	**3.05**
Control Room Layout	0	0	0	0	1	5	0	0	**14**	**70**	5	25	**4.15**
Ambient Noise Level	0	0	0	0	0	0	5	25	**13**	**65**	2	10	**3.85**
Too Many External Interruptions	0	0	0	0	1	5	1	5	**12**	**60**	6	30	**4.15**
Time Constraints	1	5	0	0	0	0	3	15	**9**	**45**	7	35	**4**
Too Many Operational Mode Transitions	0	0	0	0	**8**	**40**	4	20	5	25	3	15	**3.15**
Frequency of Operational Mode Transitions	0	0	0	0	**10**	**50**	4	20	4	20	2	10	**2.9**
Too Few Crew Members Available	0	0	1	5	4	20	3	15	**10**	**50**	2	10	**3.4**
Too Many Crew Members Available	0	0	0	0	5	25	5	25	**9**	**45**	1	5	**3.3**
Too Many Items on Turnover Sheet	0	0	0	0	6	30	**10**	**50**	4	20	0	0	**2.9**
Amount of Required Unit Conversions	0	0	1	5	**7**	**35**	4	20	5	25	3	15	**3.1**
Too Many Procedures	1	5	0	0	6	30	3	15	**7**	**35**	3	15	**3.2**
Inadequate Procedures	1	5	0	0	3	15	1	5	**9**	**45**	6	30	**3.75**
# of Concurrently Used Procedures	0	0	0	0	1	5	0	0	**12**	**60**	7	35	**4.25**
Conflicting Procedures	0	0	0	0	1	5	5	25	4	20	**10**	**50**	**4.15**
Variety of Procedures	0	0	0	0	**7**	**35**	6	30	**7**	**35**	0	0	**3**

	Not Applicable	%	Strongly disagree	%	Disagree	%	Undecided	%	Agree	%	Strongly agree	%	Response average
Too Few Steps in Procedures	1	5	2	10	**7**	**35**	5	25	4	20	1	5	**2.6**
Too Many Steps in Procedures	1	5	0	0	4	20	7	35	**7**	**35**	1	5	**3.1**
Too Many Check Points	1	5	0	0	6	30	5	25	**8**	**40**	0	0	**2.95**
Too Few Crew Members Required to Execute Procedure	0	0	1	5	**7**	**35**	3	15	**7**	**35**	2	10	**3.1**
Too Many Crew Members Required to Execute Procedure	0	0	0	0	5	25	6	30	**9**	**45**	0	0	**3.2**
Too Few Information Sources to Make an Assessment	0	0	1	5	6	30	1	5	**10**	**50**	2	10	**3.3**
Too Many Information Sources to Make an Assessment	0	0	0	0	**11**	**55**	1	5	7	35	1	5	**2.9**
Level of Assessment Effort	0	0	0	0	3	15	5	25	**10**	**50**	2	10	**3.55**
Team Unfamiliarity	0	0	2	10	5	25	4	20	**7**	**35**	2	10	**3.1**
Shift Length	0	0	2	10	3	15	5	25	**7**	**35**	3	15	**3.3**
Inadequate Simulator Training	1	5	2	10	2	10	2	10	**7**	**35**	6	30	**3.5**
Inaccurate Simulator Training	1	5	1	5	2	10	2	10	**8**	**40**	6	30	**3.65**
Inadequate Communication	0	0	0	0	0	0	1	5	**13**	**65**	6	30	**4.25**
Too Few HSI Panels	1	5	0	0	6	30	4	20	**7**	**35**	2	10	**3.1**
Too Many HSI Panels	0	0	1	5	3	15	7	35	**8**	**40**	1	5	**3.25**
Variety of HSI Panels	0	0	0	0	5	25	2	10	**11**	**55**	2	10	**3.5**
Panel Too Small	1	5	0	0	2	10	**8**	**40**	7	35	2	10	**3.3**
Panel Too Large	1	5	0	0	7	35	**9**	**45**	3	15	0	0	**2.65**

	Not Applicable	%	Strongly disagree	%	Disagree	%	Undecided	%	Agree	%	Strongly agree	%	Response average
Too Few Redundant Panels	0	0	1	5	**9**	**45**	5	25	5	25	0	0	**2.7**
Too Many Redundant Panels	0	0	0	0	4	20	**10**	**50**	6	30	0	0	**3.1**
Too Few Control Devices	0	0	1	5	**9**	**45**	4	20	5	25	1	5	**2.8**
Too Many Control Devices	0	0	0	0	2	10	6	30	**10**	**50**	2	10	**3.6**
Variety of Control Devices	0	0	0	0	4	20	3	15	**10**	**50**	3	15	**3.6**
Too Few Redundant Control Devices	0	0	0	0	**10**	**50**	5	25	5	25	0	0	**2.75**
Too Many Redundant Control Devices	0	0	0	0	**7**	**35**	5	25	**7**	**35**	1	5	**3.1**
Too Few Control Devices Shared by Different Systems	**17**	**85**	0	0	1	5	0	0	1	5	1	5	**0.55**
Too Many Control Devices Shared by Different Systems	1	5	0	0	5	25	3	15	**8**	**40**	3	15	**3.3**
Variety of Colors Used for Functional Groupings	1	5	2	10	4	20	3	15	**8**	**40**	2	10	**3.05**
Clutter (in displays or panels)	0	0	0	0	3	15	1	5	**9**	**45**	7	35	**4**
Volume of Information (in displays or panels)	0	0	0	0	2	10	3	15	**12**	**60**	3	15	**3.8**
Too Few Alarms	1	5	5	25	3	15	2	10	**8**	**40**	1	5	**2.7**
Too Many Alarms	0	0	0	0	0	0	1	5	**13**	**65**	6	30	**4.25**
Variety of Alarms	0	0	0	0	1	5	6	30	**9**	**45**	4	20	**3.8**
Amount of Inoperable Equipment	1	5	0	0	2	10	2	10	**11**	**55**	4	20	**3.7**

	Not Applicable	%	Strongly disagree	%	Disagree	%	Undecided	%	Agree	%	Strongly agree	%	Response average
Amount of Malfunctioning Equipment	1	5	0	0	1	5	3	15	**9**	**45**	6	30	**3.85**
Years Experience in Same Control Room	1	5	0	0	1	5	4	20	**10**	**50**	4	20	**3.7**
Experience in Other Control Rooms	0	0	0	0	7	35	5	25	**8**	**40**	0	0	**3.05**
Boredom	1	5	2	10	4	20	2	10	**8**	**40**	3	15	**3.15**
Cognitive Fatigue	1	5	1	5	3	15	1	5	**7**	**35**	**7**	**35**	**3.65**
Stress	0	0	0	0	1	5	4	20	**10**	**50**	5	25	**3.95**