Human-System Interface Complexity and Opacity

Part II: Methods and Tools to Assess HSI Complexity

Farzan Sasangohar
M.L. Cummings

Massachusetts Institute of Technology*

Prepared for the Nuclear Regulatory Commission
Office of Nuclear Regulatory Research

Dr. Jing Xing
Dr. Amy D'Agostino

HAL2010-03

December 2010

http://halab.mit.edu e-mail: halab@mit.edu

*MIT Department of Aeronautics and Astronautics, Cambridge, MA 02139

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 report 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 their effects on human reliability is critical for ensuring safe performance of both operators and the entire system. This report provides a novel methodology to assess the sources of complexity in the 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.

ACKNOWLEDGEMENTS

This research was funded by the United States Nuclear Regulatory Commission Office of Nuclear Regulatory Research. The views and conclusions in this report are those of the authors and do not represent an official opinion, expressed or implied, by the US Nuclear Regulatory Commission. Special thanks are extended to Dr. Kristopher Thornburg, Dr. Amy D'Agostino and Dr. Jing Xing for their insight and input. Thanks to Humans and Automation Laboratory undergraduate research assistants: Rachel Williams for her help in HERA analysis, Morrisa Brenner for her help in HERA analysis, STAMP analysis and CXSurvey and Elizabeth Stavely for her help in CXViz development.

Table of Contents

List of Figures

List of Tables

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

Part II: Methods and Tools to Assess HSI Complexity

1. INTRODUCTION

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” was 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 analog panels to large screen and digital displays (Figure 1).

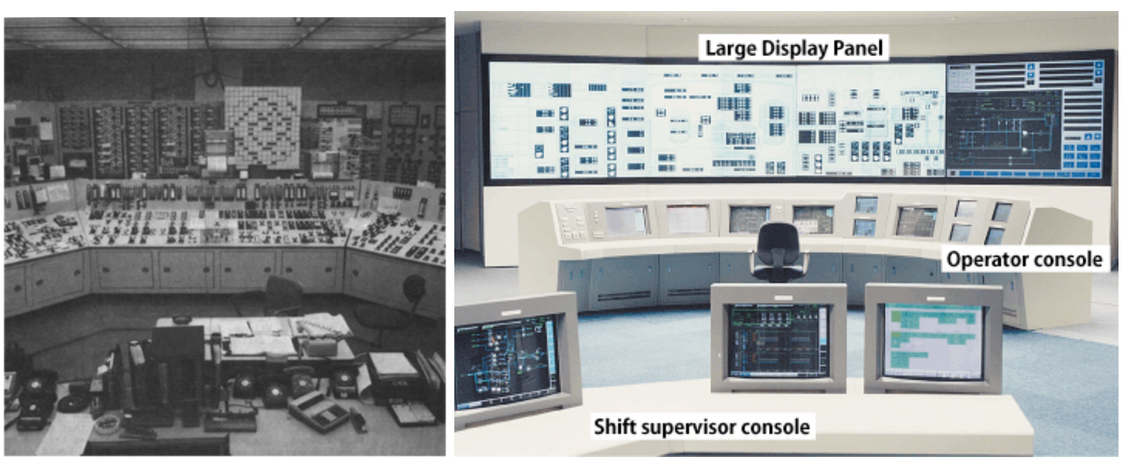


Figure 1. A traditional control room (left)[1] vs. an advanced control room (right)[2].

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. Investigating the effects of control room modernization is important since personnel in such environments must deal with increasing amounts of advanced

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

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 prescription of 'how' and 'what' information should be visualized in these new displays. 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.

Currently, the Nuclear Regulatory Commission (NRC) is responsible for the acquisition and 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 such 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.

1.1 Research Objectives

The overall objective of this research is to identify factors that contribute to complexity in new and advanced nuclear power plant systems and Human-System Interfaces (HSI). More specifically, a main objective of this report is to discuss the objective sources of complexity as perceived by operators. The addition of new computerized systems to the

NPP operations environment may have negative effects on human performance due to added perceived complexity. This report could be used to facilitate the NRC's human factors engineering reviewers in their safety and licensing activities for new and advanced control rooms by providing a technical basis to understand the nature of complexity in the NPP control rooms.

1.2 Document Organization

This document is organized into three main sections. The first section introduces perceived complexity as a problem in the next-generation NPP control rooms, motivates the importance of identifying complexity sources both objectively and subjectively, and introduces a new method to compare the objective and subjective complexity views in relation to human performance. This section also introduces several definitions of complexity and discusses different categorizations of complexity relative to the context of NPP control rooms based on an extensive literature review of different disciplines. In the second section, the methodology used to create a technical basis for complexity in NPP control rooms is described, which investigates sources of complexity both objectively and subjectively. The objective complexity information is gathered from incident report databases and the subjective complexity information is gathered from three groups of stakeholders: operators, designers and reviewers. Finally, the last section introduces two tools to gather complexity data and to compare and analyze the resulting complexity source networks.

2. LITERATURE REVIEW

In order to provide a technical basis to understand complexity in the context of NPP control rooms, an extensive literature review of different disciplines was conducted. Part I of this report (Cummings et al., 2010) includes various intellectual perspectives on the topic of complexity, which enables a better understanding of the connection between complexity and the design and evaluation of NPP control rooms as complex systems. This section summarizes the literature review.

The term “complexity” comes from the Latin word “Complexus”, which means, “to twine” as defined in the *Merriam-Webster* dictionary. 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.

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.

Table 1. Different Definitions of complexity (Modified from Xing & Manning, 2005)

SOURCE	DEFINITION
General understanding	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 interrelations
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

Interconnections describe the links between components of a system. These interconnections can be difficult to quantify in a given 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.

This generic description of complexity is useful to understand the basis of the variety of complexities that have been identified in the literature. 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. Furthermore, another important aspect of complexity, namely the “temporal” aspect of complexity, is underestimated in these investigations. Understanding the effects of time-on-task and the duration of cognitive modes on perceived complexity of the control room is missing from these efforts.

2.1 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 the 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 Section 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 a quasi-objective one. 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.

2.2 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 represent homogenous view on complexity (This assumption is discussed in section 3.1): 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.

3. OBJECTIVE VS. PERCEIVED 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.

Understanding and measuring the 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, inefficient 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.

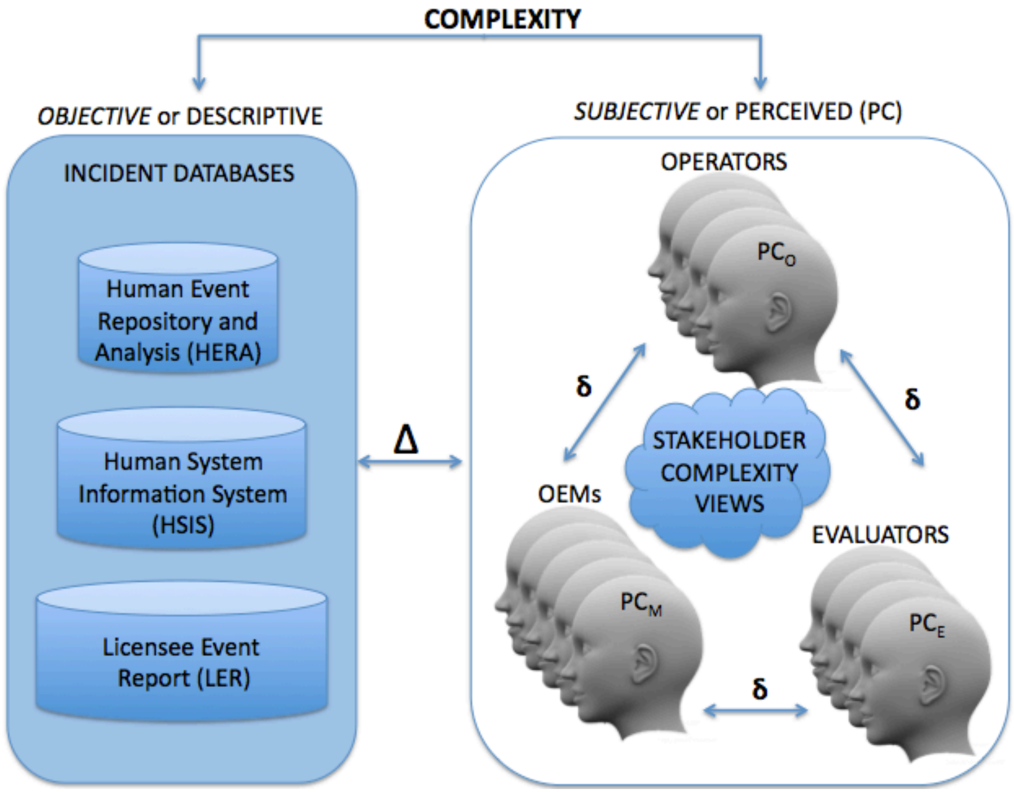


Figure 2. The differences between subjective complexity and objective complexity (Big Delta). Differences between complexity views of the control room design stakeholders (Small Deltas).

3.1 Conflicts in Stakeholder Complexity Views

As discussed in the previous section, three broad groups of stakeholders were chosen based on the important role they play with regards to complexity of the system: Operators, Original Equipment Manufacturers (OEMs) 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. OEMs are companies in charge of the design and construction of NPP control rooms. OEMs 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 a different mental model 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 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 (OEM) 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 potentially policies to align such views.

3.2 Research Questions

As previously 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 how different stakeholders view complexity (i.e., subjective complexity), and the actual world complexity (i.e., objective complexity) needs to be investigated further. This leads to three fundamental research questions:

1. How should complexity be defined in the context of NPP control rooms and more generally, in Human Supervisory Control (HSC) systems? In other words, what factors contribute to the complexity of a control room?
2. How can the effects of complexity on human performance be measured both objectively and subjectively, while considering the difference between the two?
3. How can the negative effects of complexity in NPP control rooms be mitigated or changed through design, procedures and other organizational practices?

While this report introduces a novel methodology to address the first two research questions, the third research question will be explored in future efforts.

4. METHODOLOGY

In order to address the abovementioned questions, this research introduces a methodology 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.

4.1 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 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). Finally, several subject matter experts (SMEs) 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).

4.2 HERA Analysis: An Evidence-based Approach

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.

HERA is an incident report database designed to make available empirical human performance as well as system's fault data from 22 commercial nuclear plant incidents. The incidents in HERA were chosen because they met certain criteria. For example they all reflect human performance considerations, and report a common cause failure (see NUREG/CR-6903 for a discussion of selection criteria). HERA database was originally designed by NRC researchers to support their Human Reliability Analysis (HRA) research. 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. An enormous amount of detailed information regarding each sub-event, including the event summary, key human performance insights 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 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. 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 database. As shown in Figure 3, 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. As previously discussed, each incident in HERA is subdivided into hundreds of sub-events that provide the timeline of events. Each sub-event was coded based on the type of information it contains and is sequentially numbered (e.g., XHE 1, XHE 2, etc.).

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.

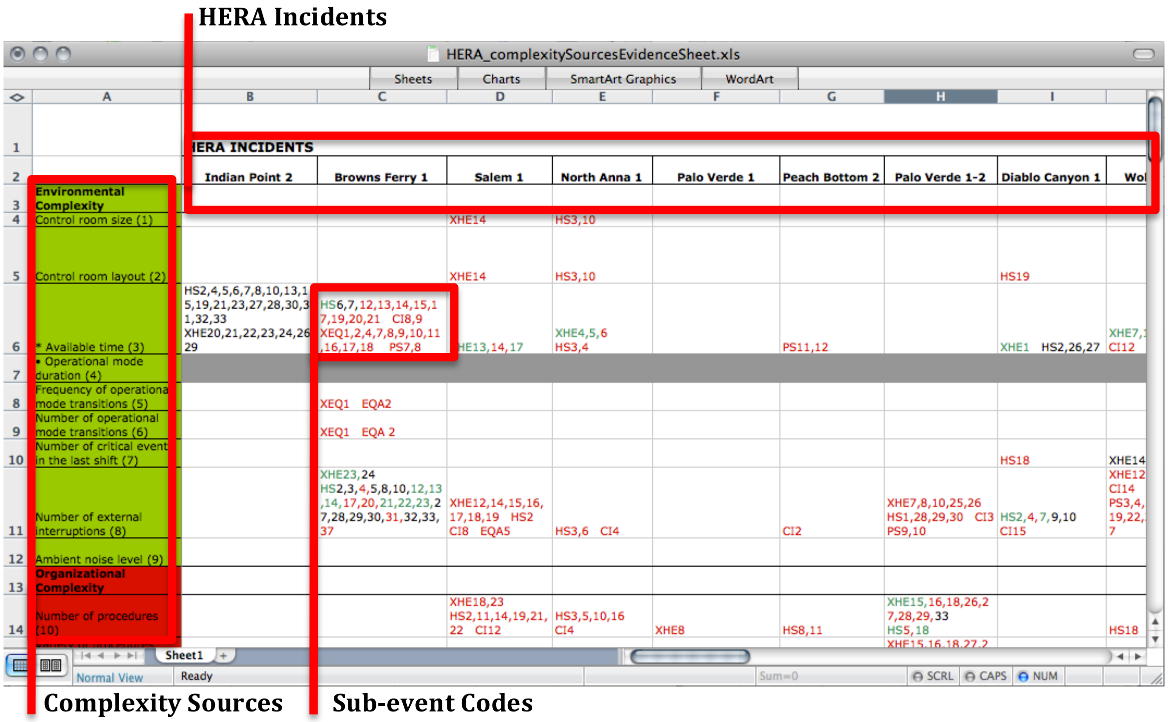


Figure 3. Complexity source evidence database.

Although HERA provides vast amount of information for each incident, a systematic investigation of these incidents that considers the interactions between the system components was not performed. 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 incidents, which has the largest number of interconnections (Appendix A). 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).

4.3 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. 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 a perfect 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

4.4 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 4). 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 5, 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 Salem 1 incident, the two nodes are connected.

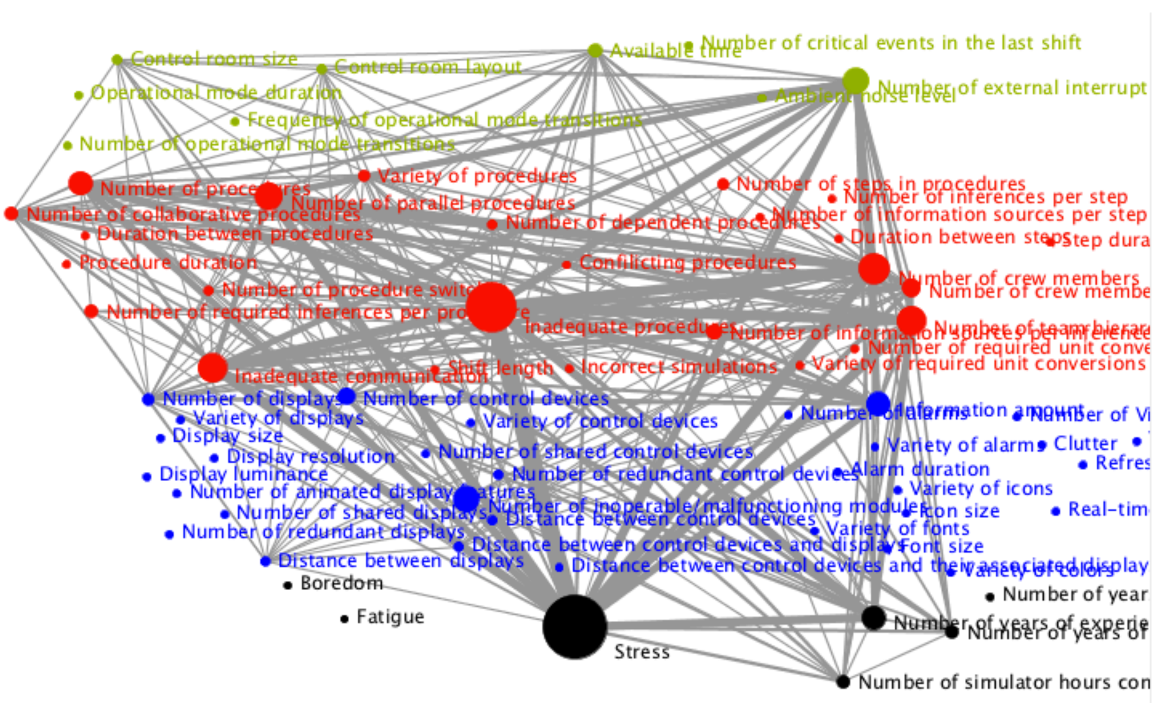


Figure 4. Complexity Source Network (CSN) for the Salem unit 1 incident.

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 3). 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 Salem 1 incident (Figure 5), 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 5).

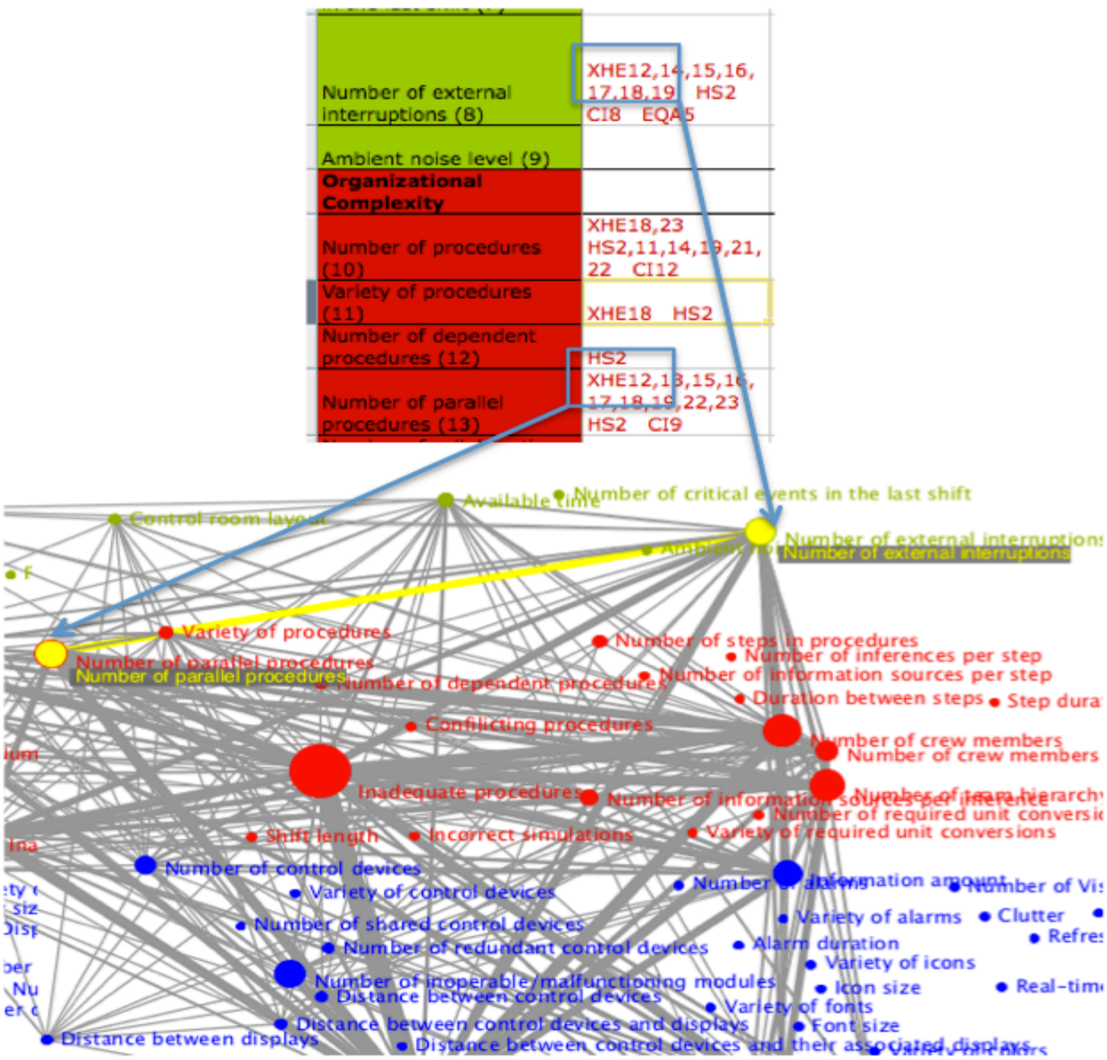


Figure 5. Interaction between the two sources of complexity "Number of external interruptions" and “Number of parallel procedures" in the Salem Unit 1 incident.

4.5 Human Supervisory Control Complexity Chain

The CSN was organized via a Human Supervisory Control (HSC) complexity chain (Figure 6). The HSC chain (Cummings and Tsonis, 2006) (Figure 7) 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.

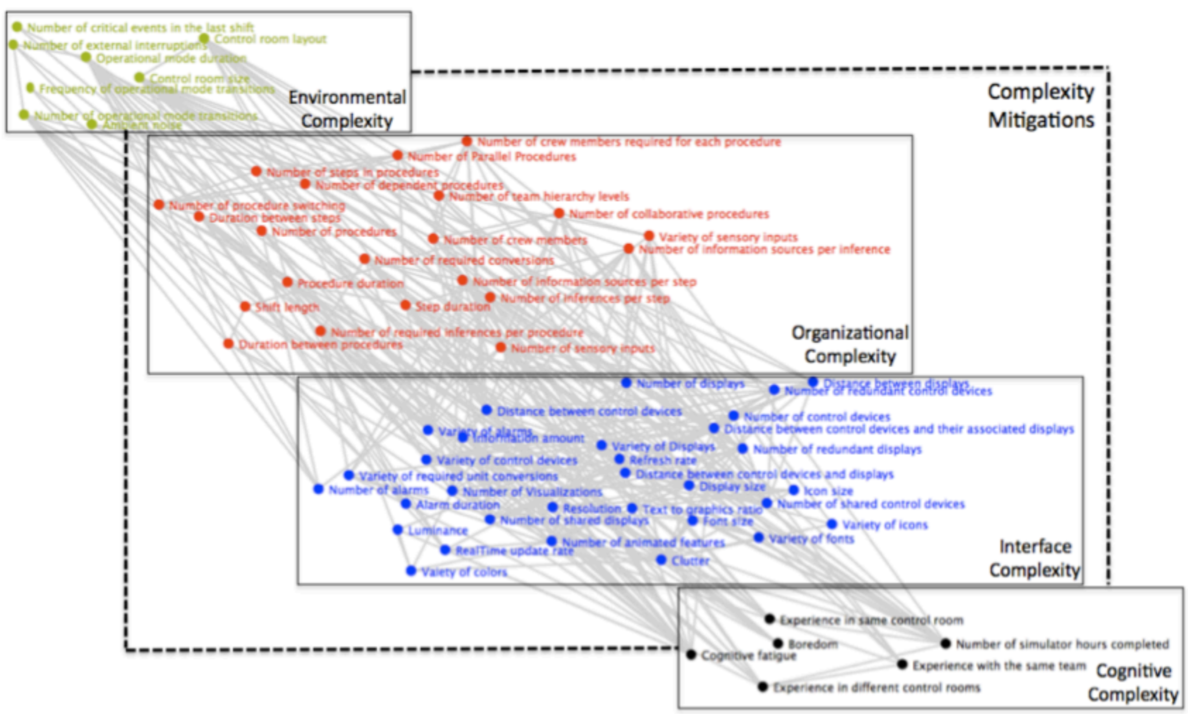


Figure 6. Complexity source network embedded in HSC complexity chain.

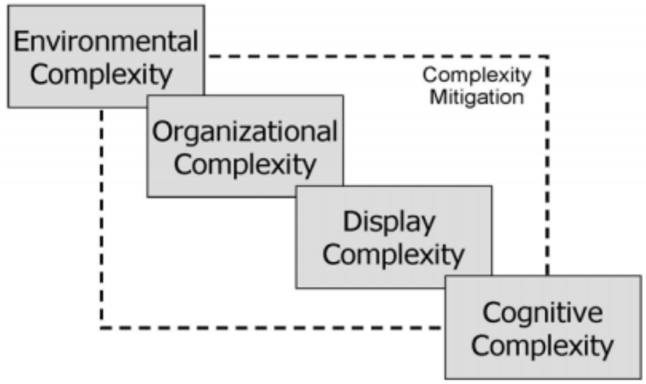
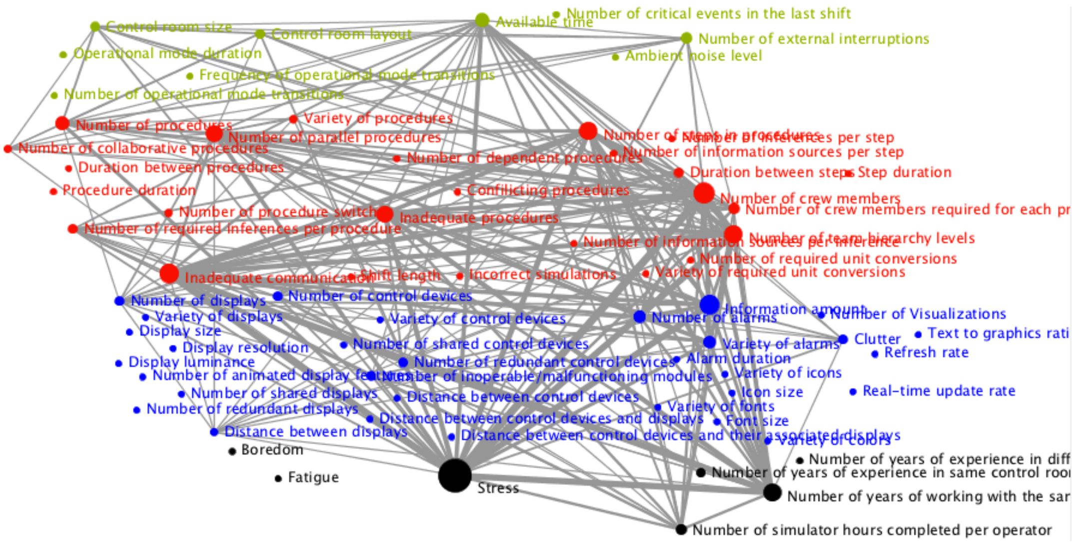


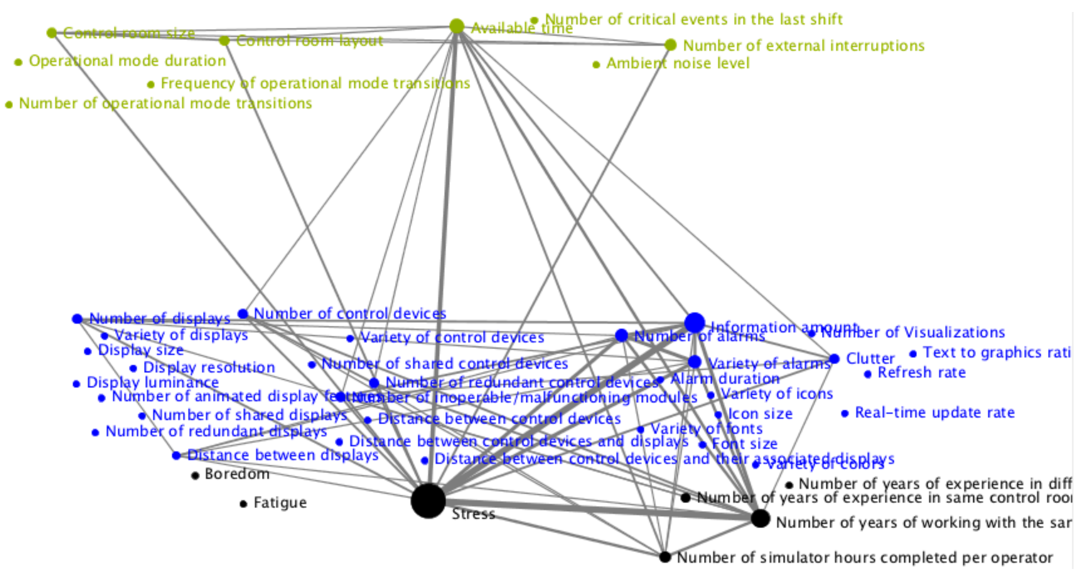
Figure 7. HSC Complexity Chain (Cummings and Tsonis, 2006, p. 4)

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 7) 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.

Using the HSC complexity chain, the effect of different layers of complexity on the overall network can be analyzed. For example, Figure 8 illustrates the effects of removing the organizational complexity layer from the CSN corresponding to North Anna unit 1 accident. 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.



(a)



(b)

Figure 8. A comparison between the North Anna unit 1 incident with (a) and without (b) organizational complexity factors.

4.6 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. CXVIZ interface has 3 main sections (Figure 9): 1) a visualization window that displays the identified sources of complexity within the Human HSC complexity chain (Cummings and Tsonis, 2006). 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), 2) a vertical toolbar, that provides several analytic functionalities. 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, and 3) a database window that allows the user to interact with the evidence database. These sections are explained in more detail in Section 5.

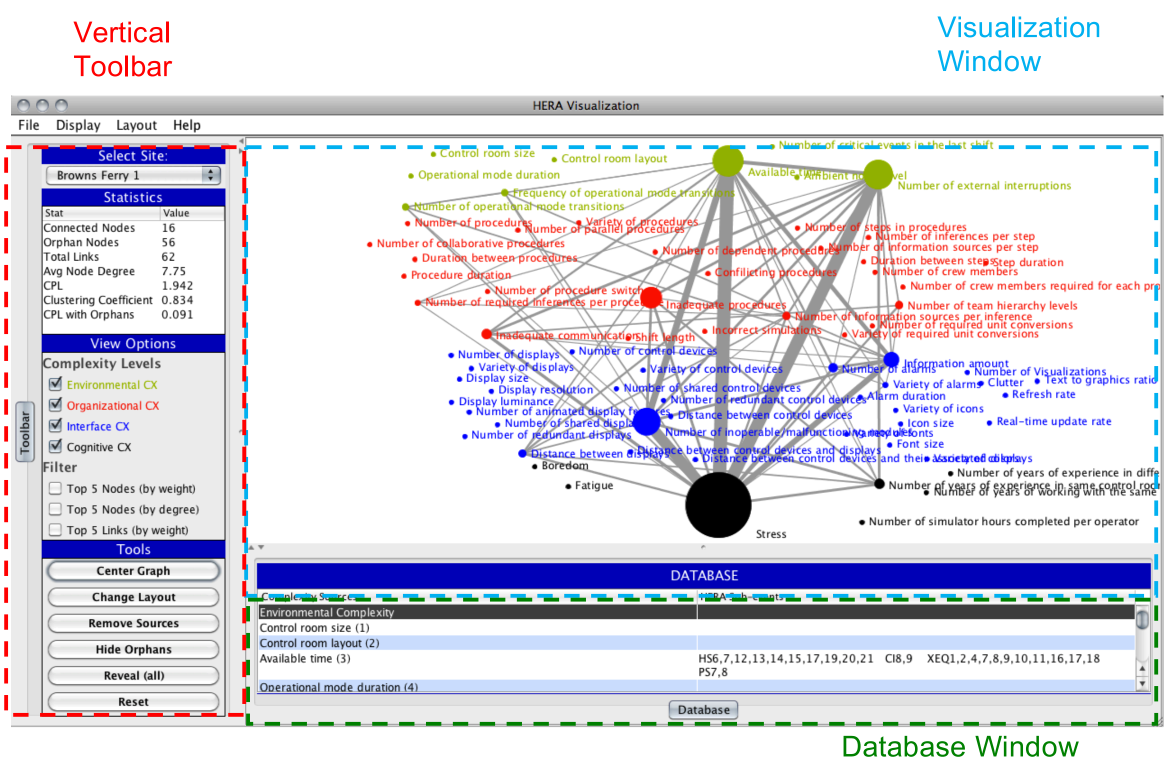


Figure 9. CXViz visualizing the CSN for Browns Ferry unit 1 accident.

Analysis

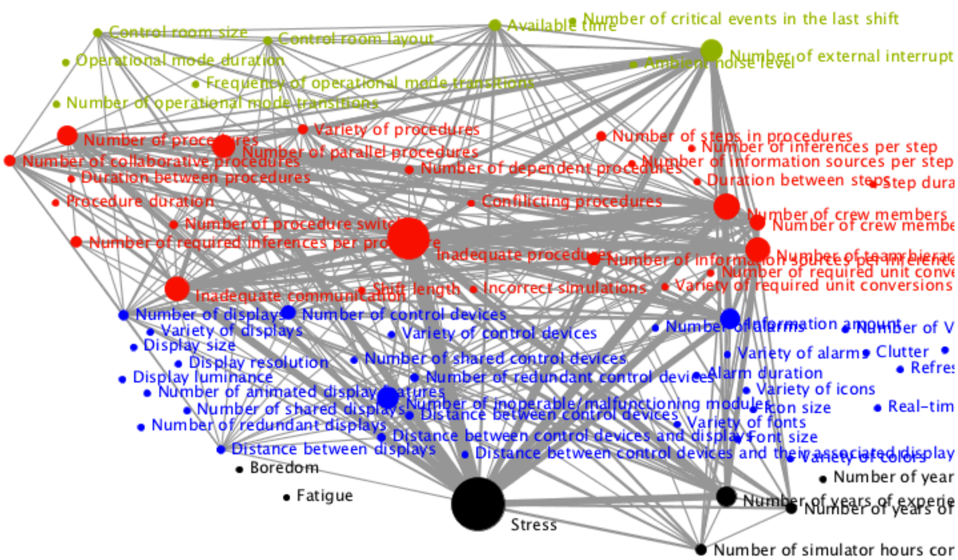
CXViz also provides several important network statistics with regards to complexity that facilitate the network analysis process. The complexity of a network is usually characterized by its non-trivial structure. In particular, "connectivity" can provide insight into the complexity of a network. Connectivity 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.

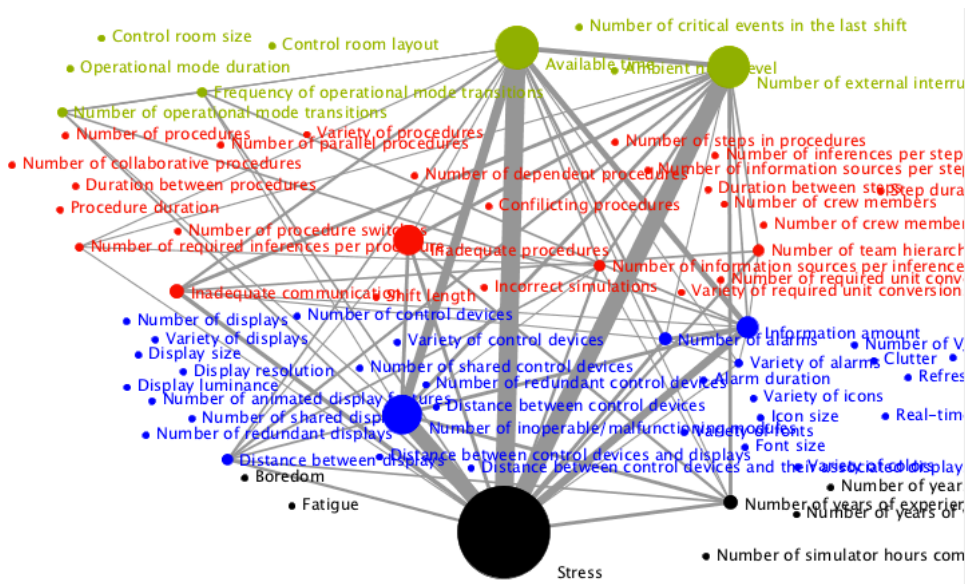
Characteristic Path Length (CPL): CPL is an important measure of network connectivity. It is calculated as the average of all the shortest paths between pairs of nodes. Ideally the CPL of CSNs should be large which means less connectivity is desired (Braha and Bar-Yam, 2004, Braha, 2007).

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 10): 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 subevents 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 10, Salem 1 CSN is more connected 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). A more detailed analysis of the 22 CSNs will be included in a future report.



(a)



(b)

Figure 10. A comparison between the network characteristics of two CSNs: Salem unit 1 (a) and Browns Ferry unit 1 (b).

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 11). 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.

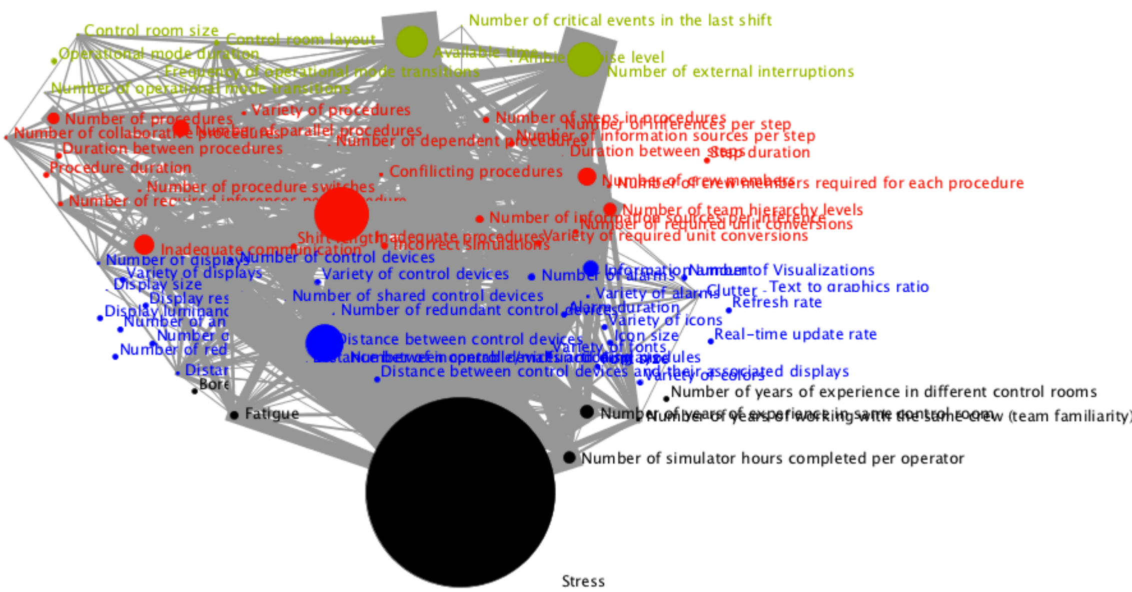


Figure 11. The aggregate CSN for incidents in HERA.

This section has presented how objective complexity, defined as that stemming from NRC-approved incident and accident databases, can be quantified. However, as previously discussed, 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.

4.7 Identification of Subjective Complexity Views

An interactive iPad® application called CXSurvey (Complexity Survey) was developed to gather subjective complexity data from various stakeholders (Figure 12). We are currently in the process of gathering subjective complexity data from three different stakeholder groups, namely operators, control room designers and NRC reviewers using the iPad-based survey-interview method. The details and screenshots of this interface are provided in the next section.

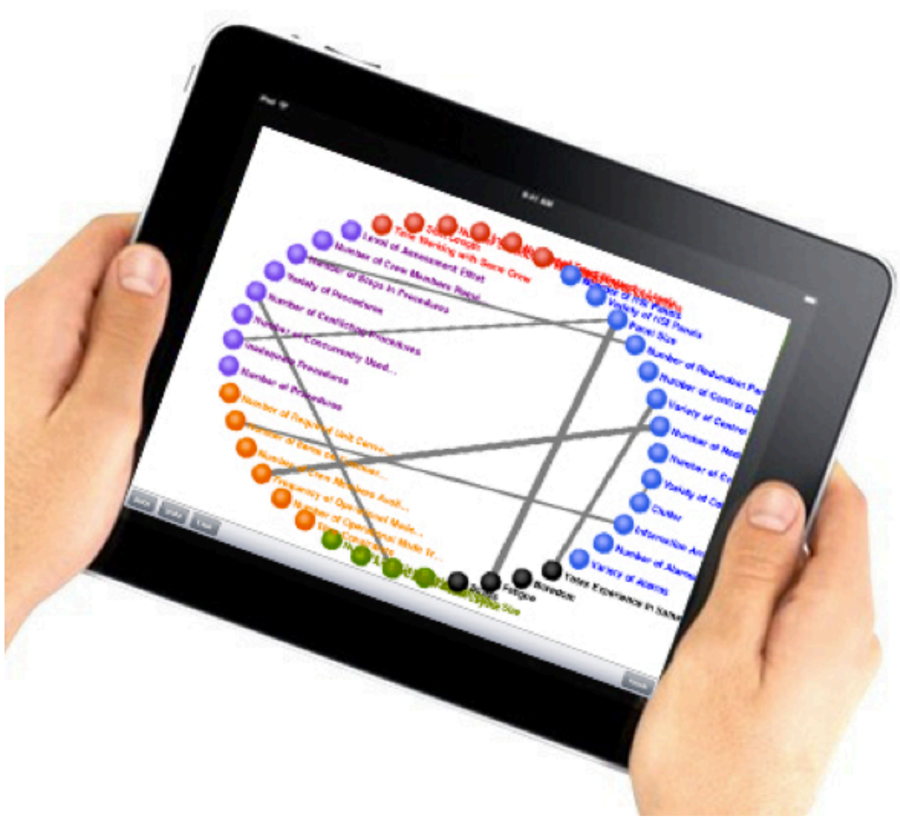


Figure 12. CXSurvey interface on the iPad platform.

5. COMPLEXITY ASSESSMENT TOOLS

In order to support objectives of this research, a software package called *CXBundle* was developed that includes a network information visualization and analysis tool called CXViz, and an iPad application called CXSurvey which allows researchers to gather subjective complexity views. In this section, we discuss these tools in more detail.

5.1 CXViz

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[3] 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 13):

- Menu bar
- Vertical toolbar
- Database window
- Visualization window
- Side-by-side network displays (not shown in Figure 13)

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

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

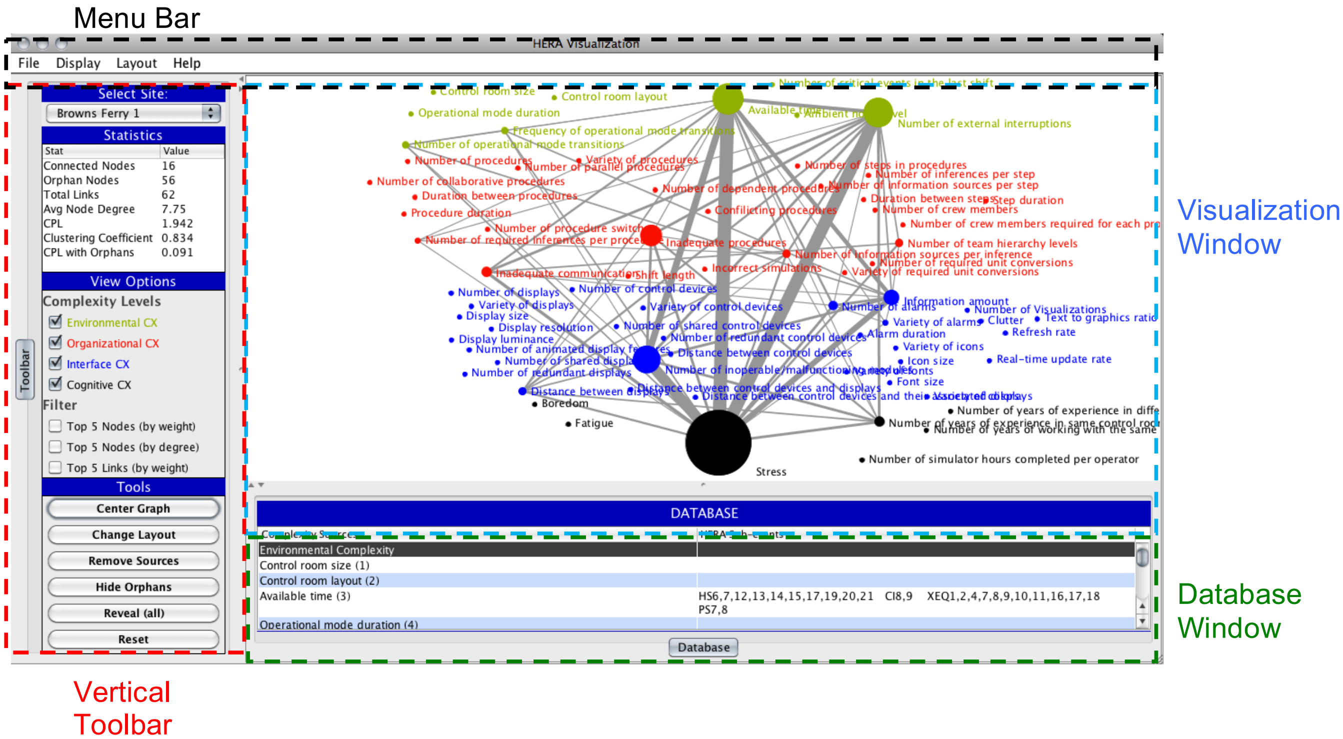


Figure 13. The CXViz interface.

5.1.1: 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 14).

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.

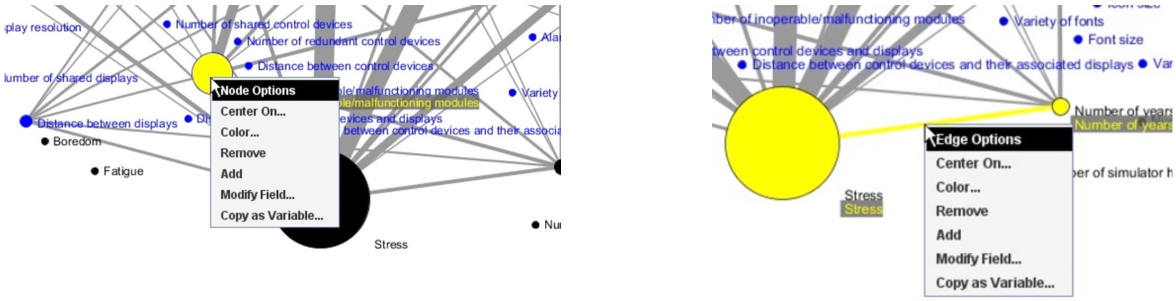


Figure 14. Modifying nodes (left) or links (right)

5.1.2: 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 15).

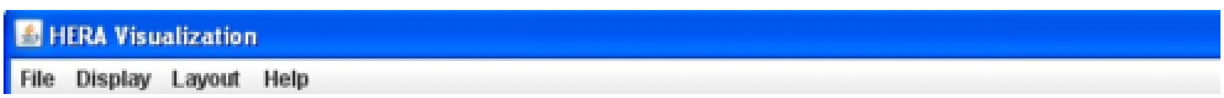


Figure 15. Menu bar

File

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

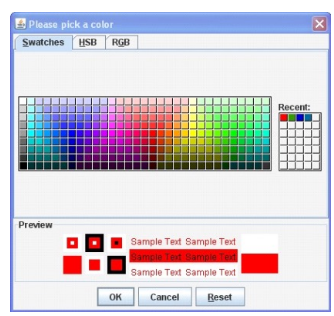


Figure 16. Color selection

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 16).

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 17). Currently, ten algorithms are provided. These are Bin Pack, GEM, Circular, Physics, Kamada-Kawai, Fruchterman-Rheingold, Spring, MDS, Random and Radial. Table 3 summarizes the definition of each algorithm.

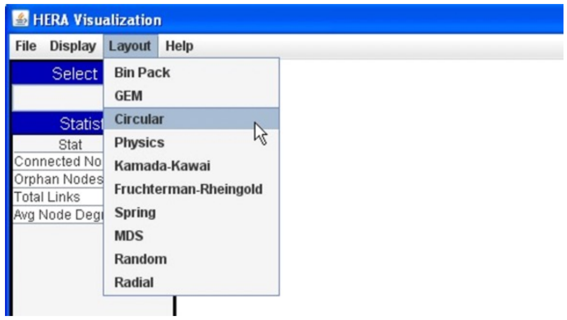
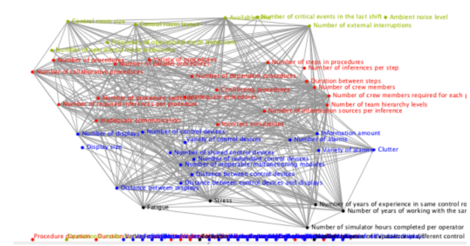
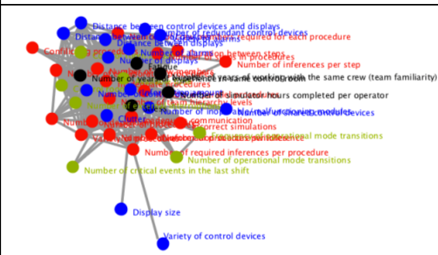
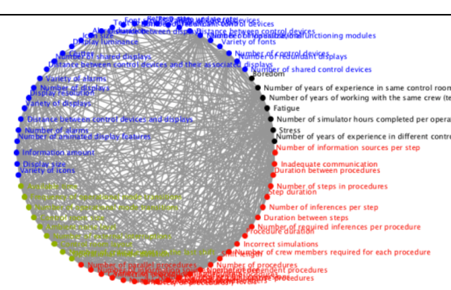
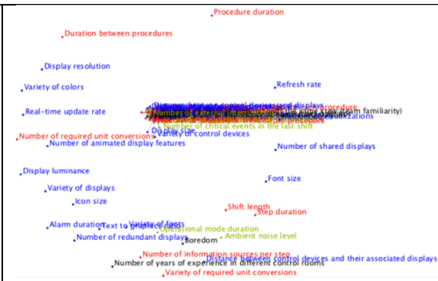
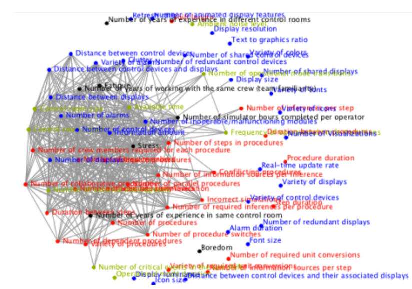
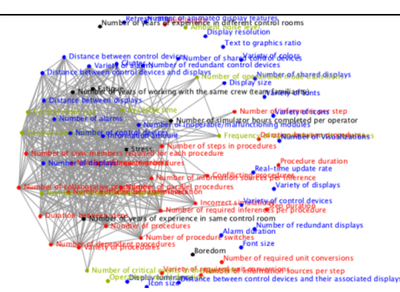
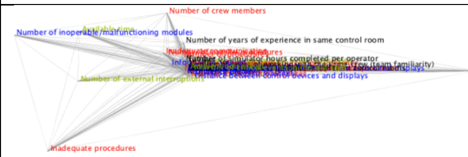
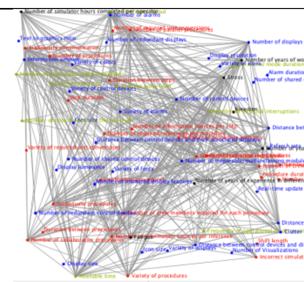
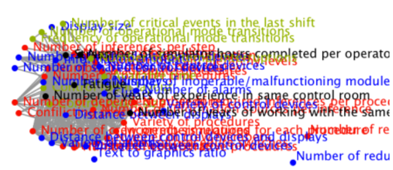


Figure 17. Layout algorithms

Table 3. 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 18).

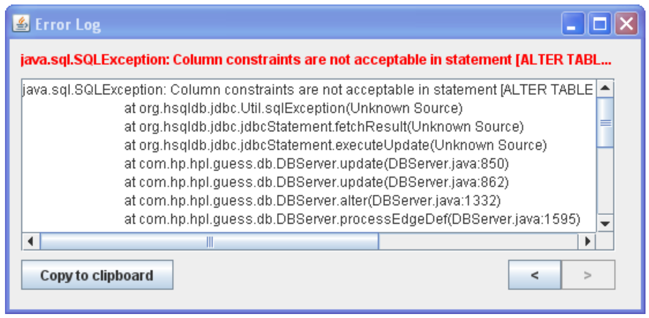


Figure 18. Error log window

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

5.1.3: The Vertical Toolbar

This vertical panel on the left side of the applet in Figure 11 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 19). 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.

Figure 19. Site selector

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 4 for the aggregate network terminology.

1. The aggregate network without weights, including the LER data (coded as no-weight or "Aggregate-NW_LER", Figure 20).
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 21).
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 22).
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").

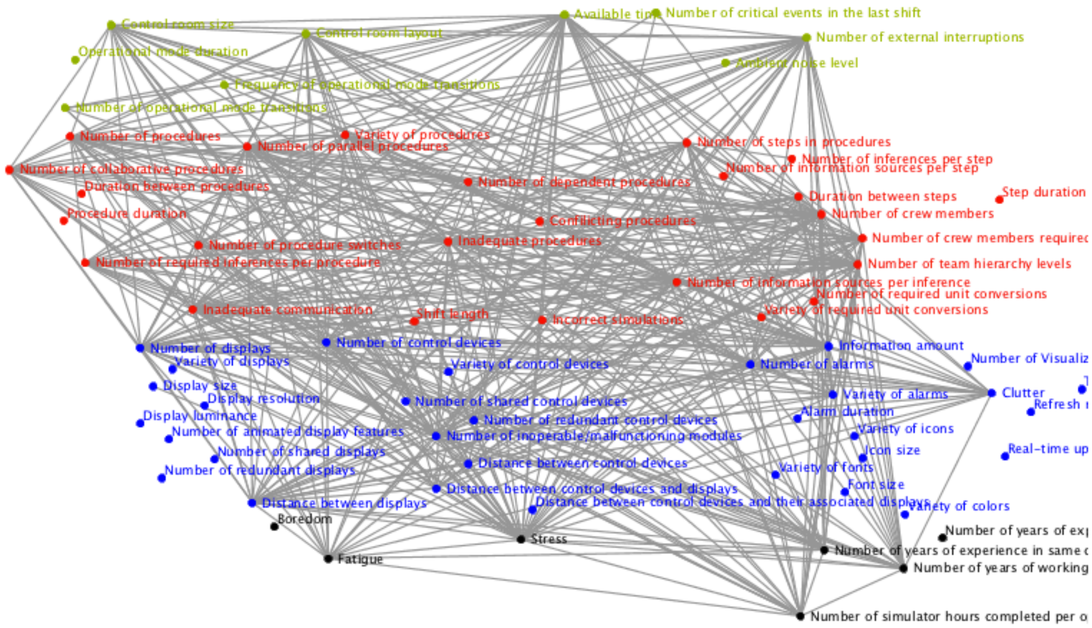


Figure 20. Aggregate no-weight network with LER data

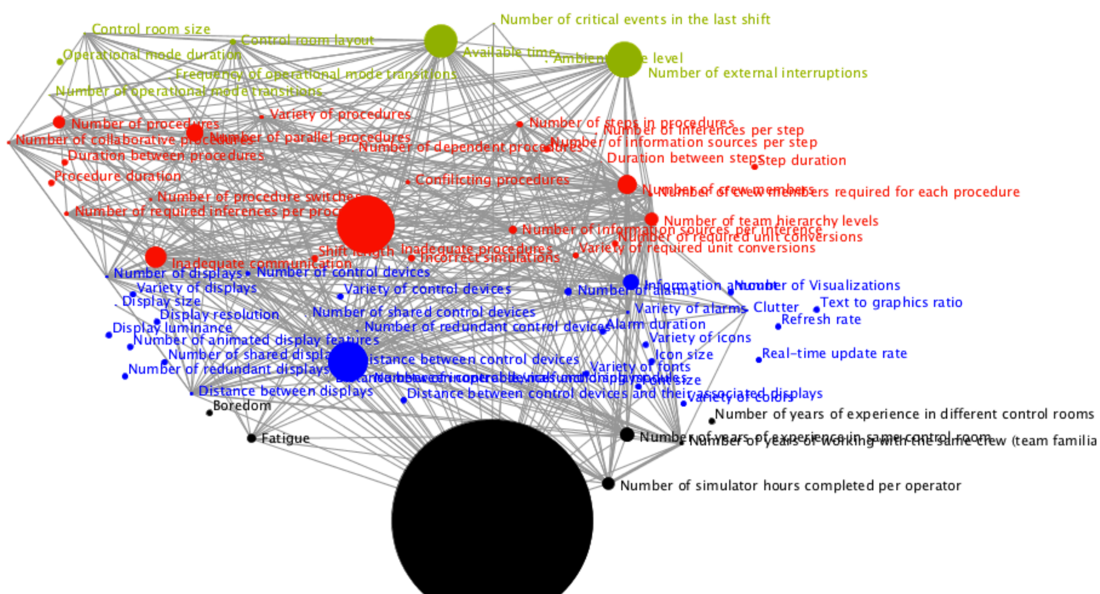


Figure 21. Aggregate half-weight network with LER data.

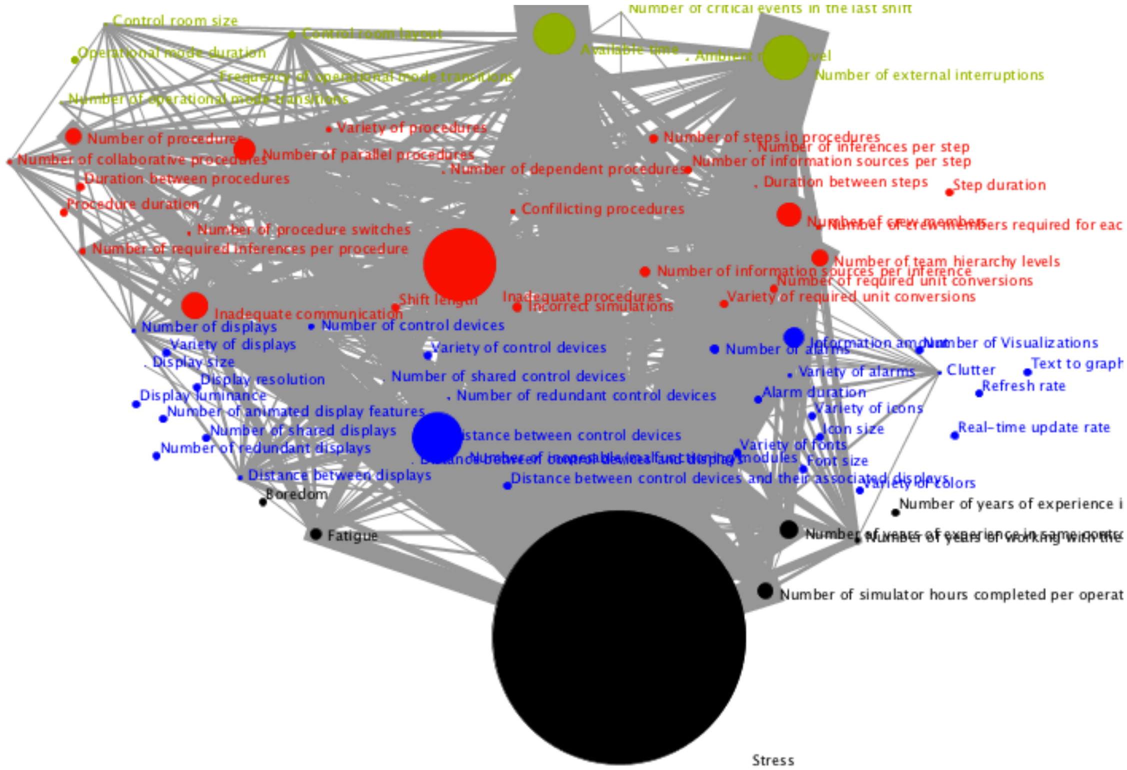


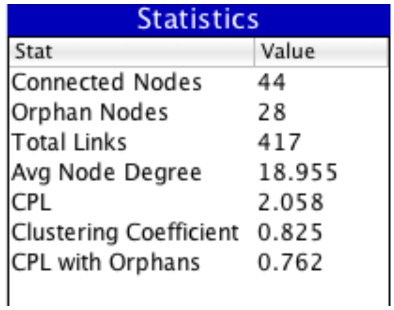
Figure 22. Aggregate full-weight network with LER data

Table 4. 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 23). 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 5 summarizes these 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 23. Statistics section

Table 5. 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 24).

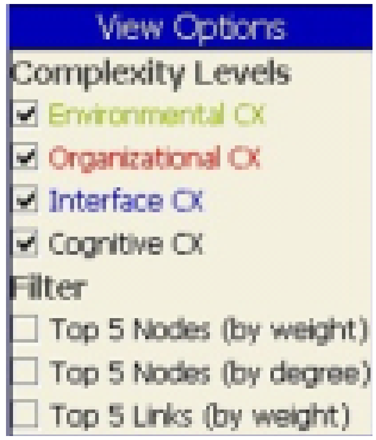
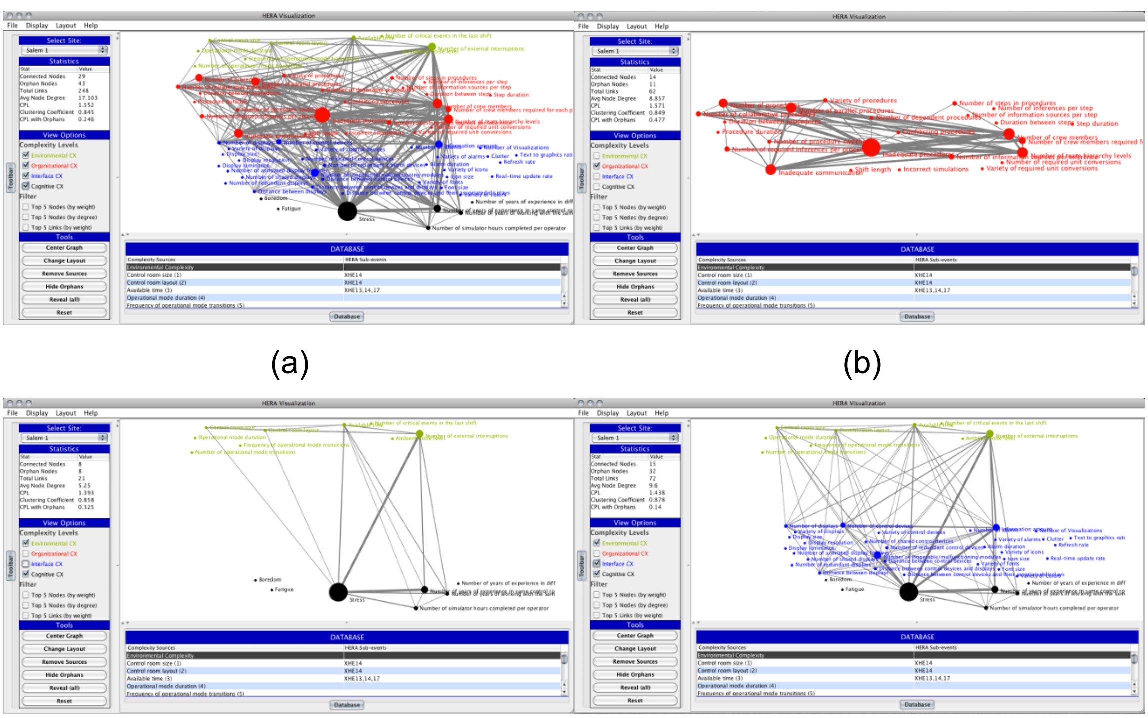


Figure 24. View options

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 25).



(a) (b)

(c) (d)

Figure 25. 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 6. Figure 26 shows the situation in which all three filters were used for the “Browns Ferry 1” incident.

Table 6. 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.	

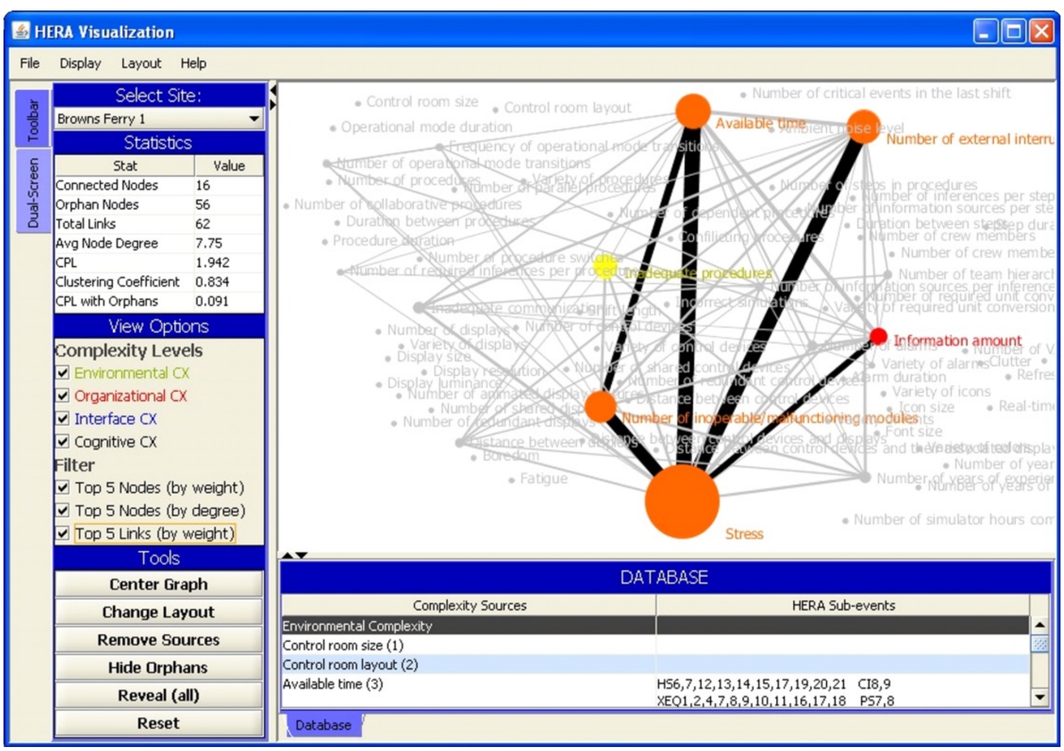


Figure 26. Using filter view options

Tools

The function buttons in the “Tools” box control the graphical window and allow the user to manipulate the chosen network (Figure 27).

Figure 27. 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 28). Similar to the layout option in the menu bar, the user can choose an algorithm to impose on the currently loaded network (see Table 3). 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.

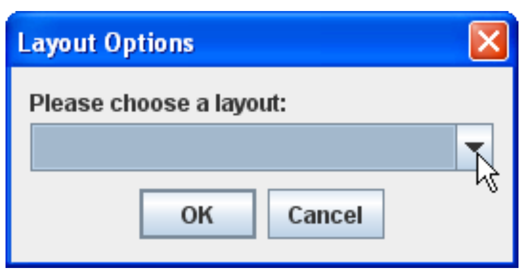


Figure 28. Layout options window

- **Remove Sources**: brings up a dialog box asking the user for the criteria that should be used to remove nodes (Figure 29).

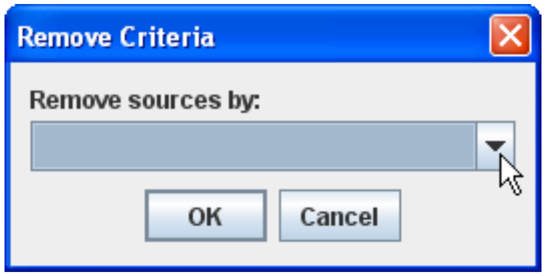


Figure 29. Remove source window

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 30.

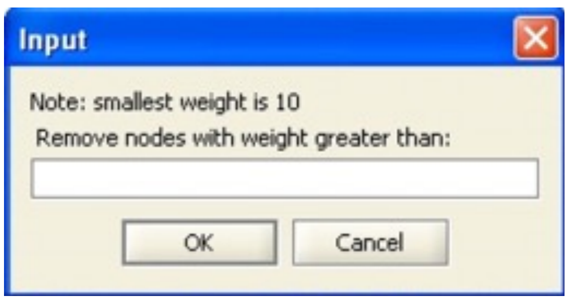


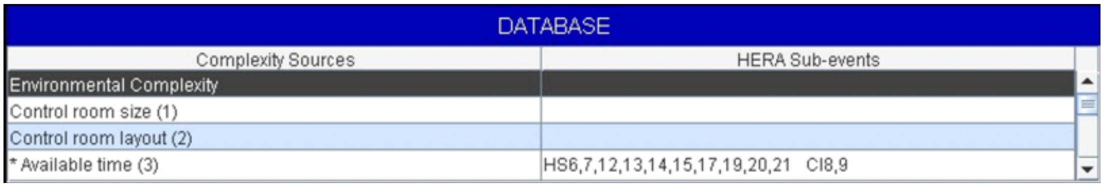
Figure 30. Filter by node weight

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

5.1.4: 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 31). 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.



DATABASE	
Complexity Sources	HERA Sub-events
Environmental Complexity	
Control room size (1)	
Control room layout (2)	
* Available time (3)	HS6,7,12,13,14,15,17,19,20,21 CI8,9

Figure 31. 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.

5.1.5: 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.

While the objective complexity is analyzed using derivative data from HERA, there is currently no way to embed the subjective views of the various stakeholders. The next section discusses a tool that is used to gather subjective complexity data from different stakeholder groups that will be embedded in the current version of CXViz.

5.2 CXSurvey

In order to gather subjective complexity data from the stakeholders, a digital survey was developed (Appendix D). 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 on a database and are transformed into CXViz format for further analysis.

Sampling

A number of SMEs with NPP operation experience (e.g., operators, instructors, supervisors), as well as NRC reviewers and OEM designers have been identified and are being interviewed. Since identifying participants in these categories is challenging, random selection is not possible, therefore, several non-probability sampling methods were used. First, NRC provided a convenience sample for operators and NRC reviewers. Next, a 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.

Procedure

Using CXSurvey, the interviewees are first asked to review a consent form (Appendix C), and then they are asked to provide their demographic information (section 5.2.1). Next, the interviewees review, rate (section 5.2.2) and rank (section 5.2.3) the identified sources and update the list if necessary. Next, a unique CSN appears based on the ratings provided, and the interviewees are asked to identify important interactions (links) between such sources that they perceive as contributing to accidents or job difficulties (section 5.2.4). The resultant CSN would feed into CXViz for further analysis. Lastly, each interviewee answers a series of open-ended questions regarding sources of complexity and potential complexity mitigations (section 5.2.5). A post-survey interview is conducted to understand the rationale behind specific choices made during the survey.

5.2.1: Demographic Information

In this section, the interviewee provides information about the stakeholder category they best represent (Figure 32). The interviewee can choose one or more options from: Active SRO (Senior Reactor Operator), Former SRO, Active RO, Former RO, and NRC Reviewer. An "Other" option was provided to let the interviewee describe his or her role if the provided options were not adequate. A "Designer" option was not provided since the control design tasks are distributed among several teams of engineers and system designers who do not necessarily call themselves designers. After data is collected, the researcher can re-categorize participants based on their input.

Figure 32. The stakeholder categories

5.2.2: Complexity Source Rating

In this part, interviewees are asked to rate the 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 is provided to let the interviewee identify the sources that are not relevant to complexity of NPP control room environments (Figure 33). Additional definitions and examples are 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).

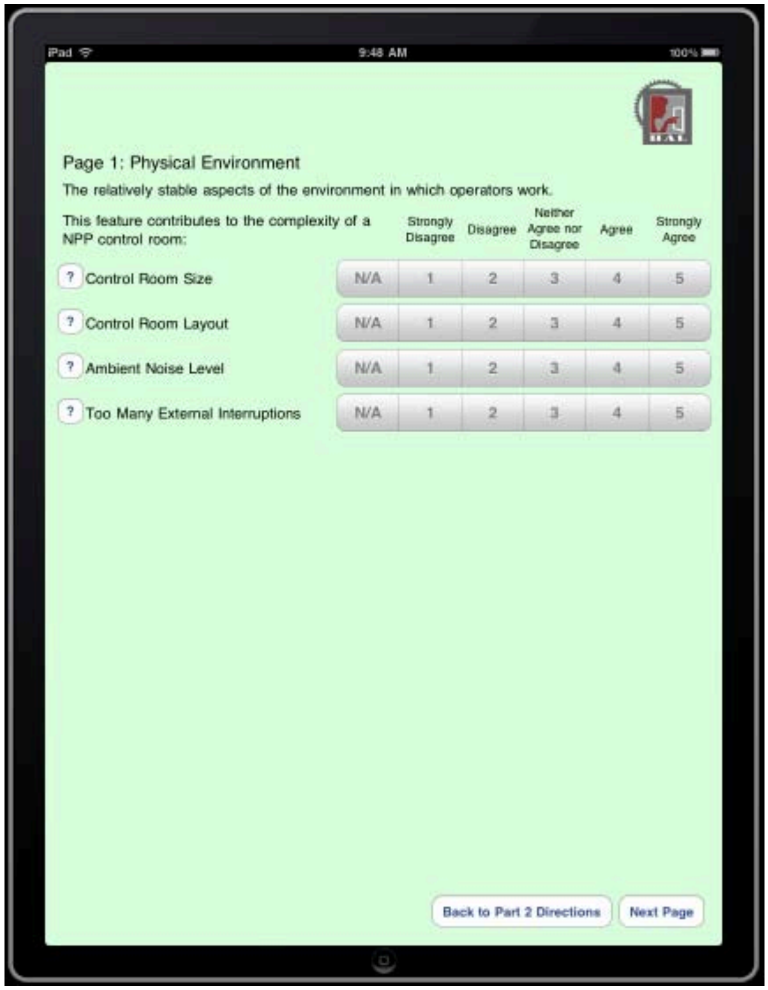
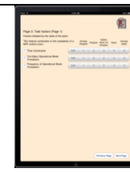


Figure 33. Complexity source rating for the physical environment

In order to improve the comprehensibility of this part and to manage the level of cognitive effort required to compare different sources, 6 different categories of sources are used (see Table 7 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.

Table 7. Complexity source categories

Complexity Category	Definition	Background Color
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	

5.2.3: Complexity Source Ranking

In this part, the interviewees rank the sources of complexity that they thought contributor 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 34).

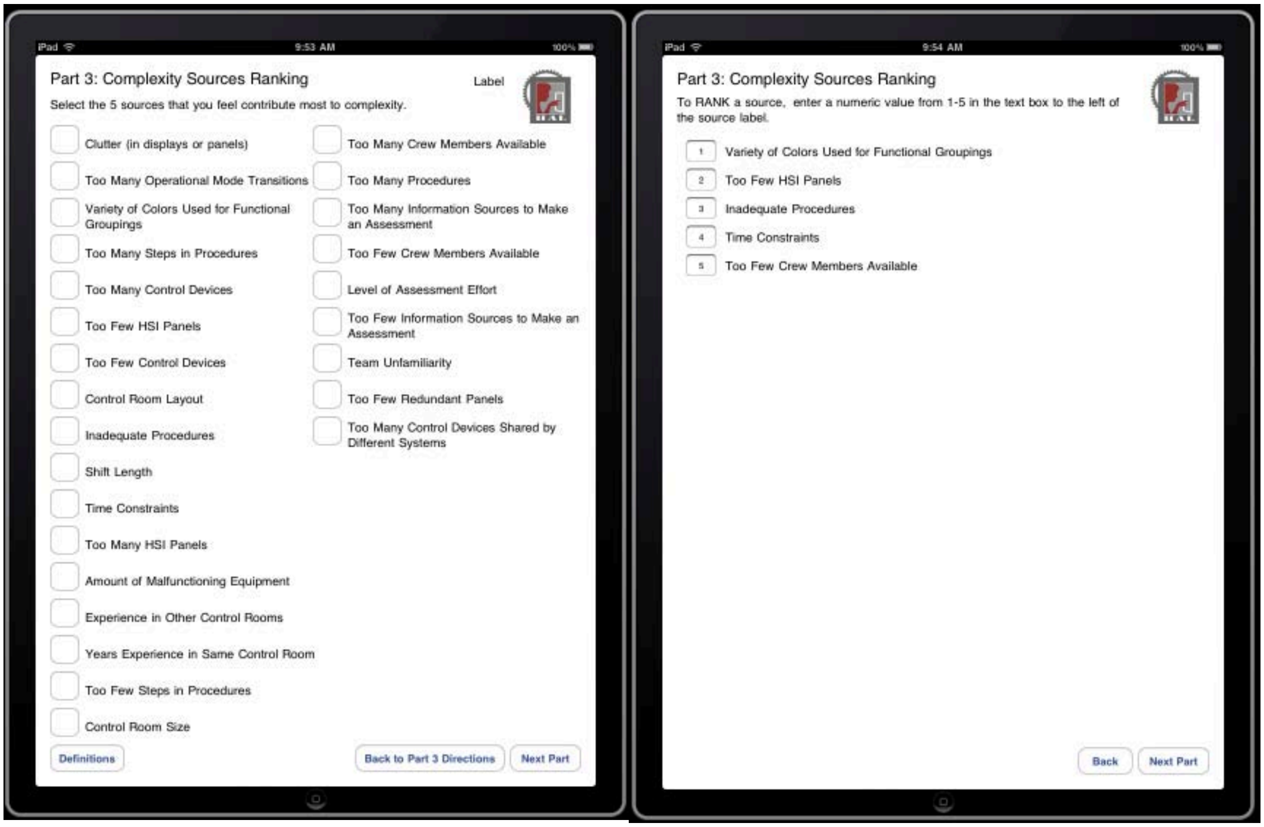


Figure 34. Complexity source ranking. Choosing top 5 (left) and Ranking the top 5 (right)

5.2.4: Identifying Interactions

In this part, interviewees are asked to identify the interactions between the identified sources of complexity. First an explanation is provided to prepare the interviewee for this section (Figure 35a). Next, based on their source ratings, the interview sees a complexity source network emerging in a circular format (Figure 35b). Interviewees can interact with the interface to rotate the network and are asked to identify pairwise links between nodes in terms of their combination of effects in an incident. In order to draw a link between two nodes, the interviewee clicks on the nodes in order. After a link is created, the interviewee is 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.

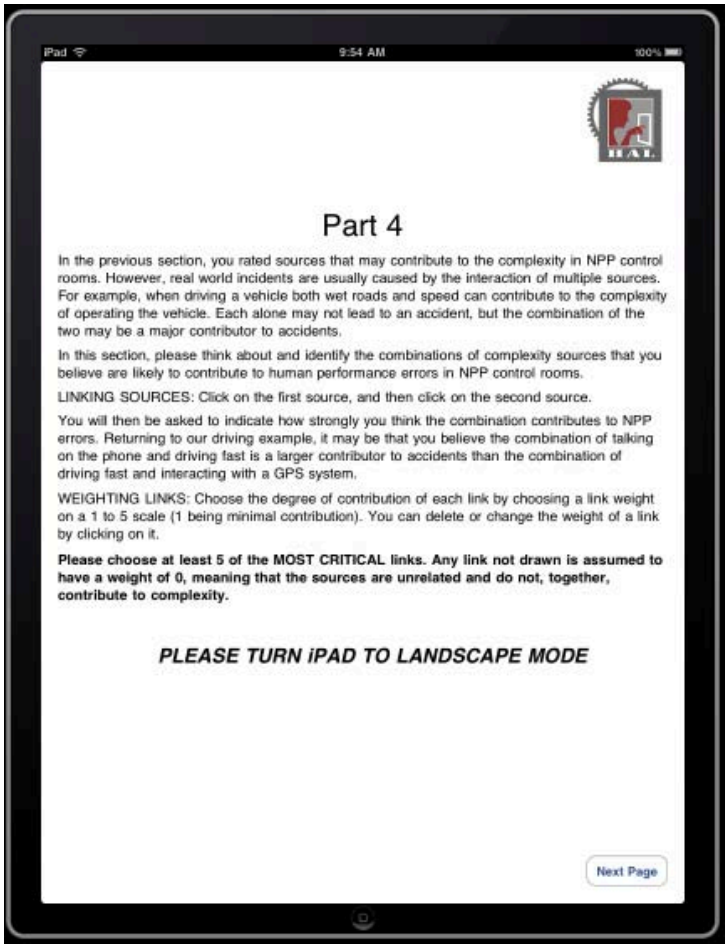


Figure 35a.The instructions for choosing complexity source interaction

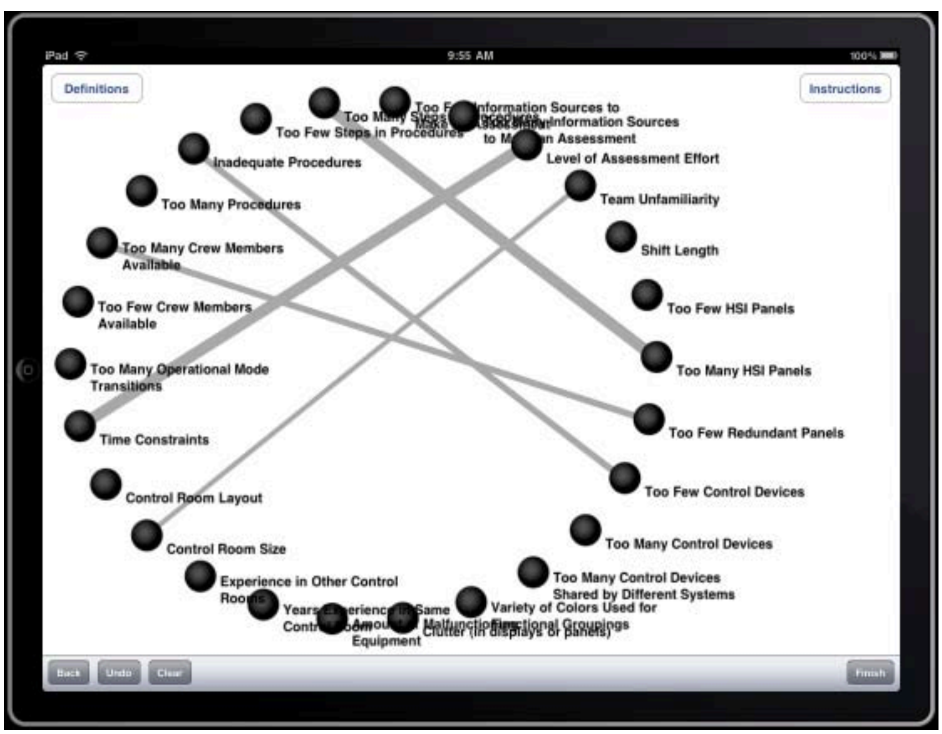


Figure 35b. An example CSN for choosing complexity source interactions

5.2.5: The open-ended questions

In this part, the interviewee responds to a series of open-ended questions. First the interviewee is asked to identify other potential sources of complexity. Next, they are asked to suggest potential complexity mitigations. Lastly they are asked to provide any additional feedback or comments. The interviewer then uses the gathered data to ask more specific questions about the interviewee's answers.

Although several tools have been designed to analyze networks or to gather subjective opinions, there have been very few tools that are designed specifically to serve the purpose of complexity analysis of socio-technical systems. In this section, we described a set of tools (CXBundle) that supports this research in visualizing and analyzing the objective complexity (CXViz) of NPP control room, as well as to gather subjective complexity data (CXSurvey) from different stakeholders. The tools were bundled to facilitate the comparison between the objective and subjective complexity data. Currently the ensemble of networks (22 CSNs from HERA incidents) is being analyzed through CXViz. In addition, several stakeholder groups were identified and a survey interview using the CXSurvey is under way. The result of the data analysis will be included in a future report.

6. CONCLUSION

In this research, a methodology to study objective and subjective complexity in NPP control rooms is proposed. 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 and subjective complexity sources to ensure that complexity considerations in the NPP control room designs and approval of such designs are realistic. Systematic analyses of previous incidents, an extensive literature review and operator interviews led to the generation of potential sources of complexity that contribute to human performance. Network representation was used to identify the interconnections between such sources. Measuring complexity in a network is 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 investigate this 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. We assert that 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. We propose 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. Subjective complexity data is currently being gathered from different stakeholder groups.

In order to facilitate this investigation and analysis, a complexity analysis software bundle (CXBundle) was developed that includes a network visualization and analysis tool called CXViz and a dynamic survey called CXSurvey. 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. Future work will include embedding the subjective representations in CXViz and analyzing the differentials between the objective and subjective views of complexity. Such analyses, including both quantitative and qualitative elements, will be conducted to determine what complexity mitigations could have the greatest impact on improved operator performance and overall plant safety.

7. REFERENCES

Bates, J. E., and Shepard, K. H. (1993). Measuring complexity using information fluctuation. Physics Letters, 172: 416-425

Bennett, C. H. (1990). How to Define Complexity in Physics, and Why. In Complexity, Entropy and the Physics of Information. Eds. Zurek,WH , Addison-Wesley, Redwood City California, 137-148

Bieri, J. (1955). Cognitive complexity-simplicity and predictive behavior. Journal of Abnormal and Social Psychology, 51, 263-268.

Börner, K., Chaomei C., and Boyack, K. (2003). Visualizing Knowledge Domains. In *Annual Review of Information Science & Technology* 37, ed. Blaise Cronin, 179-255. Medford, NJ: Information Today Inc./American Society for Information Science and Technology.

Braha, D., and Bar-Yam, Y. (2004). Information Flow Structure in Large-Scale Product Development Organizational Networks, to appear in Smart Business Networks, Peter Vervest, et al Eds. Chap. 8 (Springer Verlag, 2004).

Braha, D. (2007). The Topology and Dynamics of Complex Man-made Systems in Systems, Man and Cybernetics, 2007, 7, 4062-4068.

Campbell, J. L. (1988). Collapse of an Industry: Nuclear Power and the Contradictions of U.S. Policy, Ithaca, NY: Cornell University Press.

Casti, J. L. (1979). Connectivity, Complexity and Catastrophe, John Wiley, NY

Casti, J. L. (1995). Complexification. New York: HarperCollins.

Cilliers, P. (1998). Complexity and postmodernism: Understanding complex systems. Routledge, London and New York.

Ciurana, E. R. (2004). Complexidade: Elementos para uma definição," in Ensaios de complex dade 2, Carvalho,E.d. Assis; Mendonça,T, Porto Alegre: Sulina, 48-63.

Crockett, W. H. (1965). Cognitve Complexity and Impression Formation. In Haher BA (Ed.) Progress in experimental personality research .Vol. 2, pp 47-90. New York: Academic Press.

Crutchfield, J. P. and, Young, K. (1989). Inferring Statistical Complexity, Physics Review Letters, 63, 105.

Cummings, M. L. and, Tsonis, C. (2006). Partitioning complexity in air traffic management tasks. International Journal of Aviation Psychology, 16 (3), 277-295.

Cummings, M. L., Sasangohar, F. and, Thornburg, K. (2010). Human-System Interface Complexity and Opacity. Part I: Literature Review (HAL2010-01). Technical Report prepared for Nuclear Regulatory Commission.

Dent, E. B. (1999). Complexity science: A worldview shift. Emergence, 1, 5-9.

Drozdz S., Kwapien J., Speth J. and Wojcik M. (2002). Identifying Complexity by Means of Matrices. Physica A, 314, 355-361

Edmonds, B. (1995). What is complexity? - The philosophy of complexity per se with application to some examples in evolution, in F. Heylighen & D. Aerts (Eds.): The Evolution of Complexity, Kluwer, Dordrecht.

Edmonds, B. (1999). What is Complexity? The Philosophy of Complexity Per se With Application to Some Examples in Evolution. In Heylighen F & Aerts D (eds.): The Evolution of Complexity, Kluwer, Dordrecht. 1-18.

Eytan, A. (2006). GUESS: A Language and Interface for Graph Exploration, CHI 2006.

Eytan, A. and Miryung, K. (2007). SoftGUESS: Visualization and Exploration of Code Clones in Context, ICSE 2007.

Freeman, L. (2006). The Development of Social Network Analysis. Vancouver: Empirical Press.

Grassberger, P. (1986). Towards a Quantitative Theory of Self-generated Complexity, International Journal of Theoretical Physics, 25(9), 907-938

Halford, G. S., Wilson, W. H. and, Phillips, W. (1998). Processing Capacity Defined by Relational Complexity: Implications for Comparative, Developmental and Cognitive Psychology. Behavioral Brain Sciences, 21(6), 803-831.

Hallbert, B., Boring, R., Gertman, D., Dudenhoeffer, D., Whaley, A., Marble, J., Joe, J., and Lois, E. (2006). Human Event Repository and Analysis (HERA) System, Overview, NUREG/CR-6903, Vol. 1, U.S. Nuclear Regulatory Commission. Washington, D.C.

Hallbert, B., Whaley, A., Boring, R., McCabe, P., and Chang, Y. (2007). Human Event Repository and Analysis (HERA): The HERA Coding Manual and Quality Assurance, NUREG/CR-6903, Vol. 2, U.S. Nuclear Regulatory Commission. Washington, D.C.

Johnson, N. F. (2007). Two's Company, Three is Complexity: A simple guide to the science of all sciences. Oxford: Oneworld.

Kauffman, S. A. (1993). The Origin of Order. Oxford University Press, New York.

Kemeny, J. G., Babbitt B., Haggerty P. E. (1979). Report of the President's commission on the accident at Three Mile Island. New York: Pergamon.

Langton, C. (1991). Life at the Edge of Chaos. In Proceedings of Artificial Life II, Eds. Langton, C.; Taylor, C.; Farmer, J.; and Rasmussen, S., Addison-Wesley, pp: 41–91.

Lemoigne, J. L. (1995). La Modelisation des Systems Complexes. The Modeling of Complex Systems. Dunod, Paris.

Leveson, N. (1995). Safeware: System Safety and Computers. Addison-Wesley Publishing Company.

Leveson, N. G. (2009). System safety engineering: back to the future. Retrieved 8 August 2010, from http://sunnyday.mit.edu/book2.pdf.

Lombard, M., Snyder-Duch, J., and Bracken, C. C. (2002). Content Analysis in Mass Communication: Assessment and Reporting of Intercoder Reliability. Human Communication Research, 28(4), 587604.

McCabe, J. (1976). A Complexity Measure, IEEE Transactions on Software Engineering, SE-2 (1976) 308-320.

Martinez, M.E. (2001). The Process of Knowing: A Biocognitive Epistemology. The Journal of Mind and Behavior, 22(4), 407-426.

NEA/CSNI (2007). Workshop Proceedings of Future Control Station Designs and Human Performance Issues in Nuclear Power Plants, Halden, Norway, 8-10 May 2006, NEA/CSNI/R(2007)8.

O'Hara, J. M., Brown, W. S., Lewis, P. M., Persensky, J. J. (2002). Human-System Interface Design Review Guidelines. NUREG-0700 rev2. Nuclear Regulatory Commission. Office of the Nuclear Regulatory Research.

O'Hara, J. M., Higgins, J. C., Persensky, J. J., Lewis, P. M., Bngarra, J. P. (2004). Human Factors Engineering Program Review Model (NUREG-0711). U.S. Nuclear Regulatory Commission.

O'Hara, J. M., Higgins, J. C., and Brown W. S. (2009). Identification and Evaluation of Human Factors Issues Associated With Emerging Nuclear Plant Technology. Nuclear Engineering and Technology, 41 (3), 225-236.

Rescher, N. (1998). Complexity: A Philosophical Overview, New Brunswick: Transaction publishers.

Rosen, R. (1977). Complexity as a Systems Property. International Journal of General Systems, 3, 227-232.

Rouse, W. B. and Rouse, S. (1979) Measures of Complexity of Fault Diagnosis Tasks. IEEE Transactions on Systems, Man and Cybernetics, SMC-9(11), 720–727.

Sassangohar, F., Thornburg, K., Cummings, M.L., & D'Agostino, A. (2010). Mapping Complexity Sources in Nuclear Power Plant Domains. In Proceedings of Human Factors and Ergonomics Society 54th Annual Meeting. Santa Monica, CA: Human Factors and Ergonomics Society.

Schlindwein, S. L., & Ison, R. L. (2004). Human knowing and perceived complexity: Implications for systems practice. Emergence: Complexity and Organizations, 6, 19-24.

Schmidt, J. (2010). $8.3B in loans guaranteed for nuclear reactors. Retrieved 37March 1, 2010, from USA today's website: http://www.usatoday.com/tech/news/2010-02-16-obama-nuclear-power-plant_N.htm.

Simon, H. (1962). The Architecture of Complexity. Proceedings of the American Philosophical Society, Vol. 106, No. 6. (Dec. 12, 1962), pp. 467-482.

Stanton, N.A., Salmon, P., Jenkins, D., Walker, G. (2010). Human Factors in the Design and Evaluation of Central Control Room Operations. CRC Press.

Weaver, W. (1948). "Science and Complexity". American Scientist 36 (4): 536.

Weimao, K. and Börner, K. (2005). Mapping the Social Network and Expertise of "Network Science" Researchers. *Report to the U.S. National Research Council Study on Network Science*, 88-92. Washington, DC: The National Academies Press.

Whaley, A., Simpson, W., Richards, R. and Chang, Y. J. (2009). Human Event Repository and Analysis (HERA): User's Guide (NUREG/CR-6903). U.S. Nuclear Regulatory Commission. Vol 3.

Xing, J. (2004). Measures of Information Complexity and the Implications for Automation Design. Oklahoma, OK: Civil Aerospace Medical Institute.

Xing, J., and Manning, C. A. (2005). Complexity and Automation Displays of Air Traffic Control: Literature Review and Analysis. Technical Report DOT/FAA/AM-05/4, FAA Office of Aerospace Medicine, Washington, DC.

Xing, J. (2007). Information Complexity in Air Traffic Control Displays. Technical Report to Federal Aviation Administration, DOT/FAA/AM-07/26.

Xing, J. (2008). Designing Questionnaires for Controlling and Managing Information Complexity in Visual Displays." Technical Report to Federal Aviation Administration, DOT/FAA/AM-08/18.

APPENDIX A: 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

Time	Control Room			Turbine Hall	Other
	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		

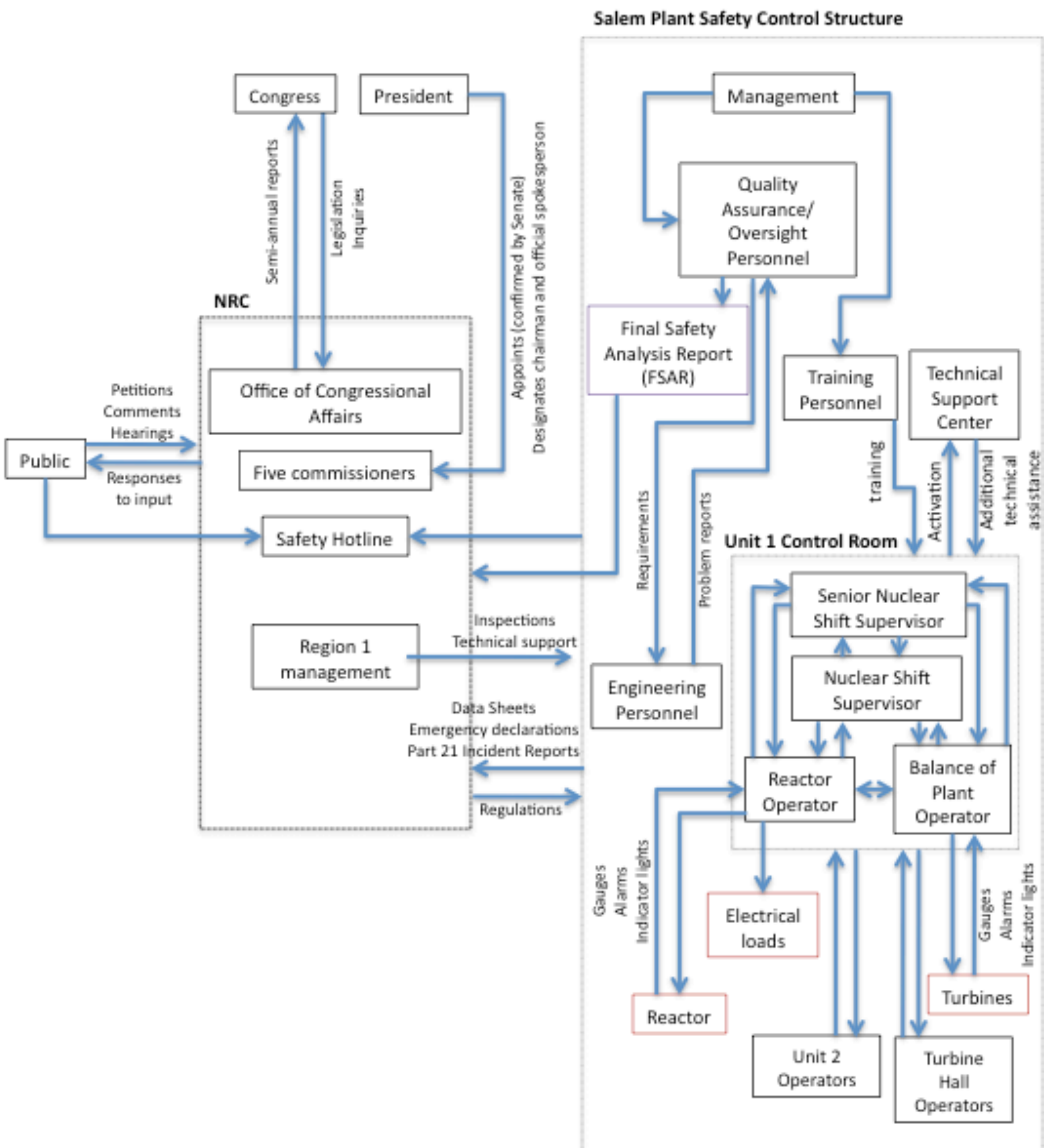
10:42 AM		Idles a feedwater pump			
10:43 AM	Begins to switch onsite electrical loads to offsite power supplies	Load reduction complete			
10:44 AM			Low-low Tave bistables trip		
10:45 AM	Finishes switching electrical loads; begins to withdraw control rods; notices Tave is below minimum critical temperature; 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 immediately closed		
1:16 PM	Begin heatup of pressurizer				Alert declared

1:36 PM					NRC enters monitoring phase of Normal Response Mode of Incident Response Plan
2:10 PM	Reestablished steam space in pressurizer				Technical 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

- **I**nadequate 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 B: LIST OF SOURCES OF COMPLEXITY

1. 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 (Changes from the original list 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: 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.

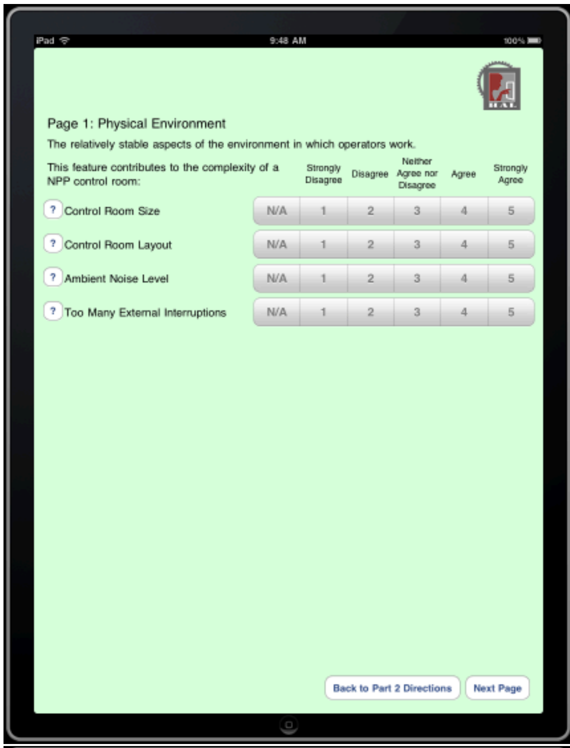
CONFIDENTIALITY

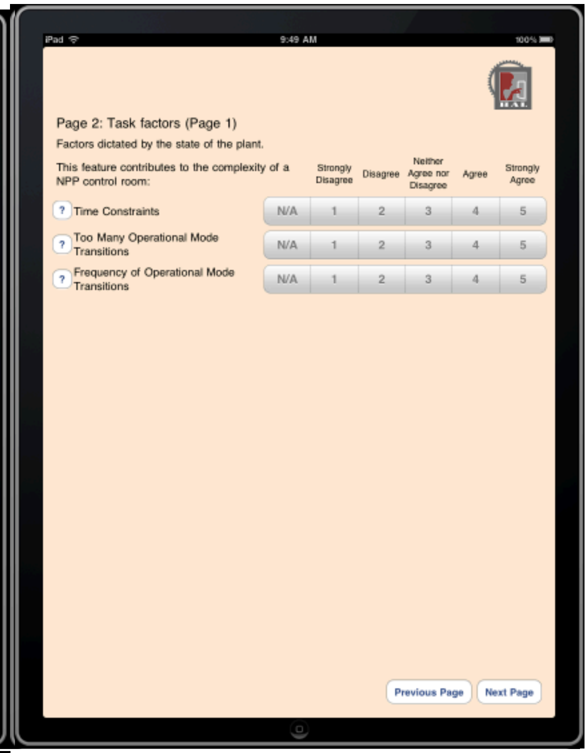
This study is anonymous. You will be assigned a subject number, which will be used in all data files to guarantee anonymity. We do not keep any information that is obtained in connection with this study and that can be identified with you.

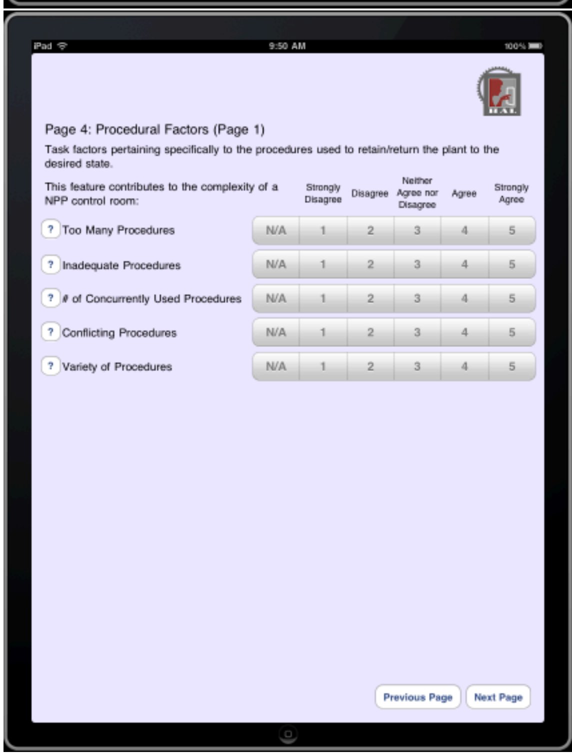
IDENTIFICATION OF **INVESTIGATORS**

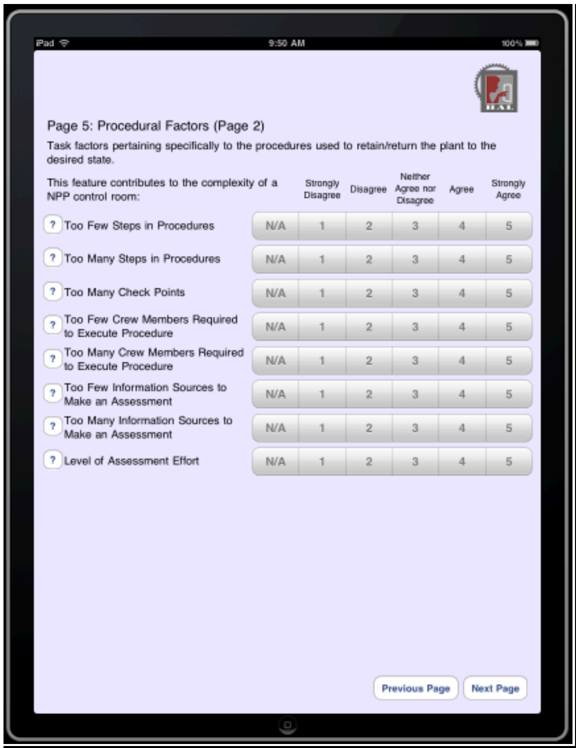
If you have any questions or concerns about the research, please feel free to contact the Principal Investigator, Mary L. Cummings, at (617) 252-1512, e-mail, missyc@mit.edu, and her address is 77 Massachusetts Avenue, Room 33-305, Cambridge, MA, 02139. The student investigator is Farzan Sasangohar and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

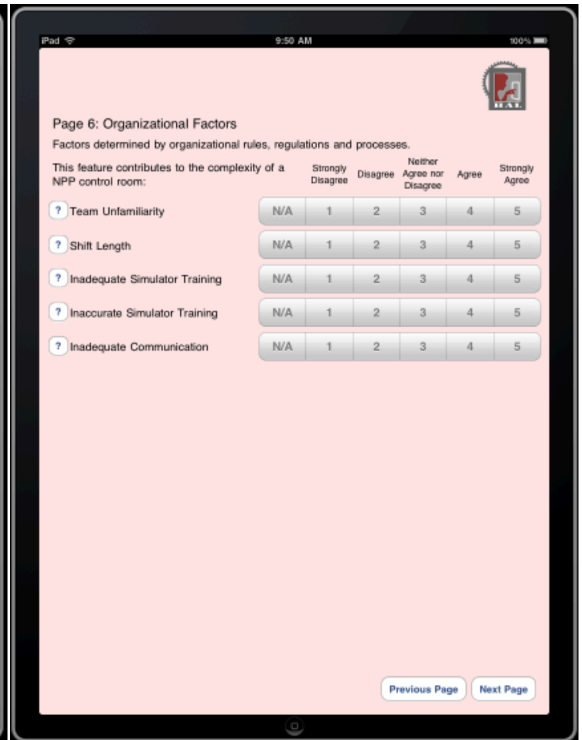
APPENDIX D: CXSURVEY SCREENSHOTS

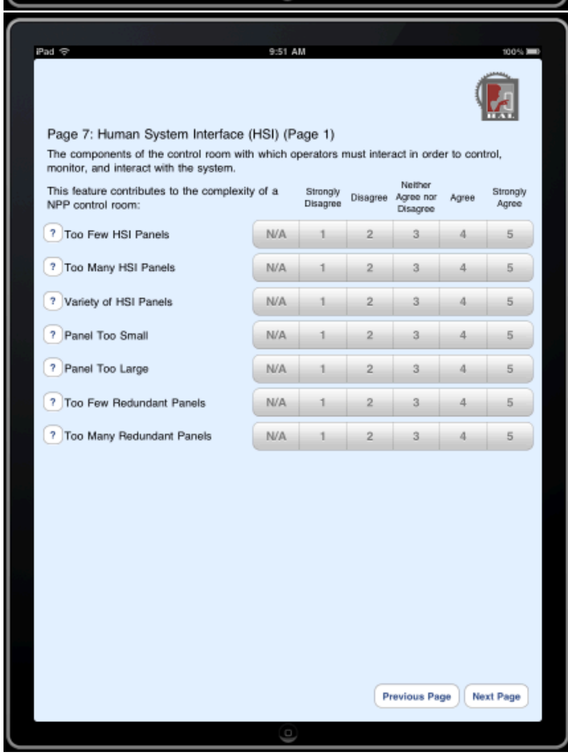

iPad
9:48 AM
100%
Page 1: Physical Environment
The relatively stable aspects of the environment in which operators work.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Control Room Size
Control Room Layout
Ambient Noise Level
Too Many External Interruptions
N/A 1 2 3 4 5
Back to Part 2 Directions
Next Page

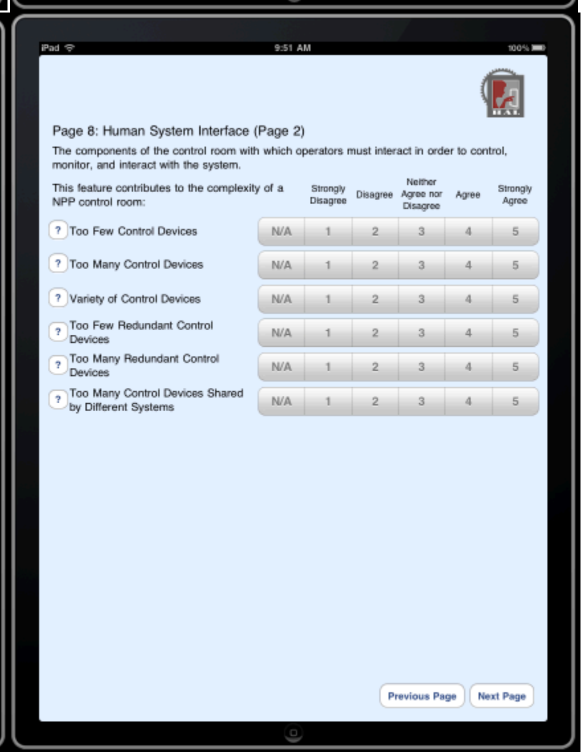

iPad
9:49 AM
100%
Page 2: Task factors (Page 1)
Factors dictated by the state of the plant.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Time Constraints
Too Many Operational Mode Transitions
Frequency of Operational Mode Transitions
N/A 1 2 3 4 5
Previous Page
Next Page

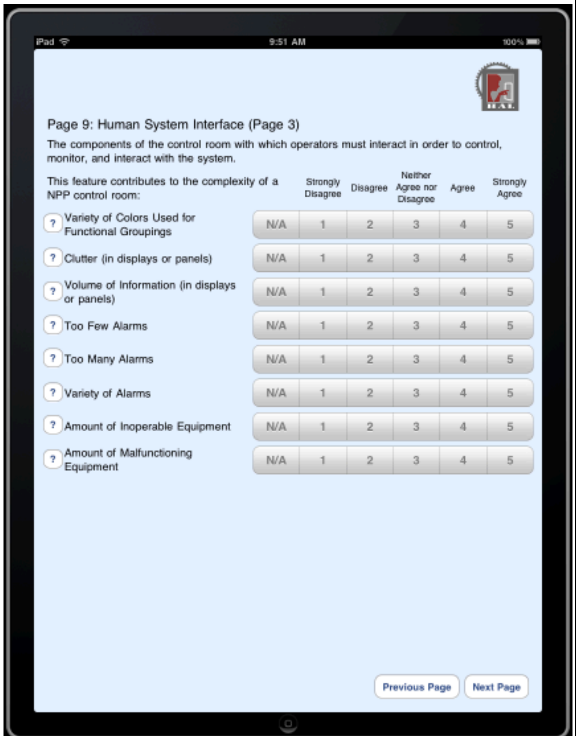

iPad
9:50 AM
100%
Page 4: Procedural Factors (Page 1)
Task factors pertaining specifically to the procedures used to retain/return the plant to the desired state.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
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


iPad
9:50 AM
100%
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

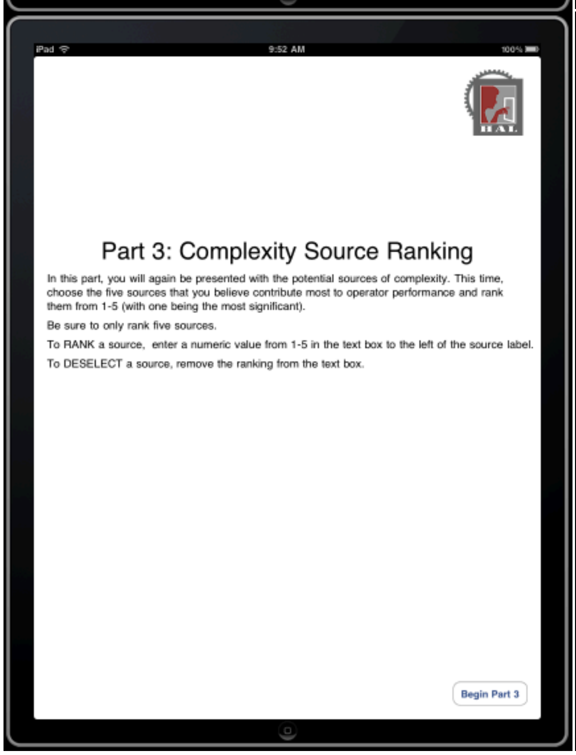

iPad
9:50 AM
100%
Page 6: Organizational Factors
Factors determined by organizational rules, regulations and processes.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Team Unfamiliarity
Shift Length
Inadequate Simulator Training
Inaccurate Simulator Training
Inadequate Communication
N/A 1 2 3 4 5
Previous Page
Next Page

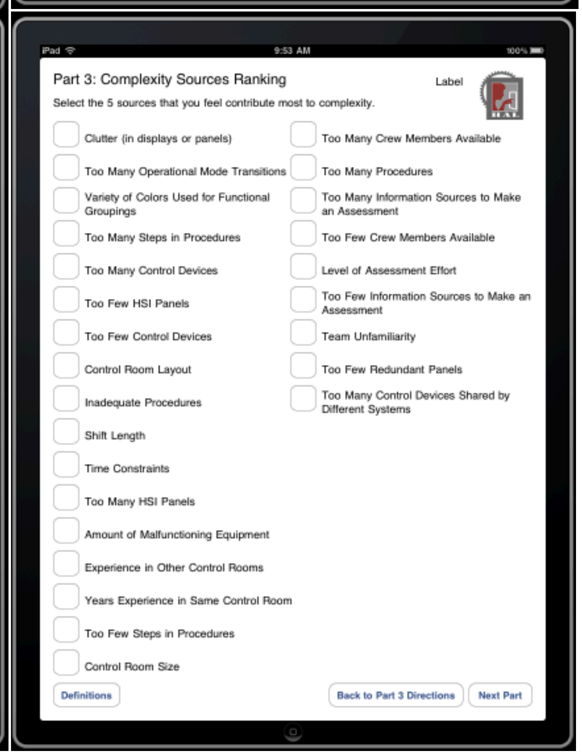

iPad
9:51 AM
100%
Page 7: Human System Interface (HSI) (Page 1)
The components of the control room with which operators must interact in order to control, monitor, and interact with the system.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
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
N/A 1 2 3 4 5
Previous Page
Next Page

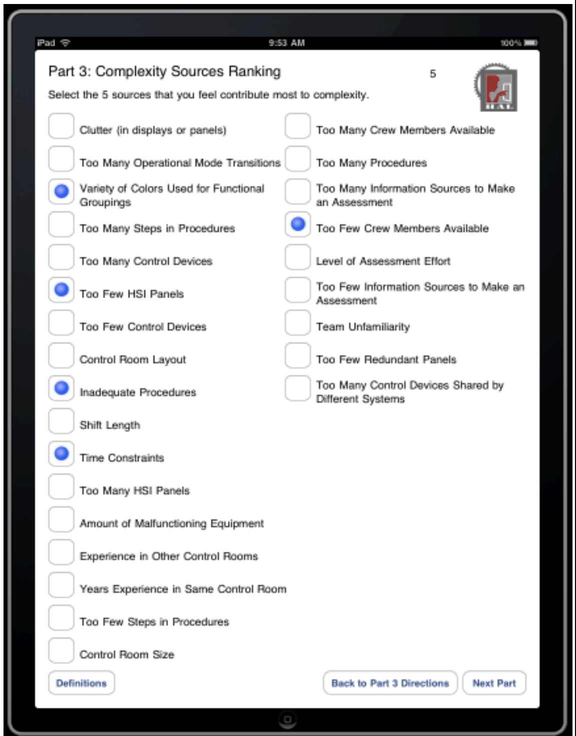

iPad
9:51 AM
100%
Page 8: Human System Interface (Page 2)
The components of the control room with which operators must interact in order to control, monitor, and interact with the system.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
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
N/A 1 2 3 4 5
Previous Page
Next Page

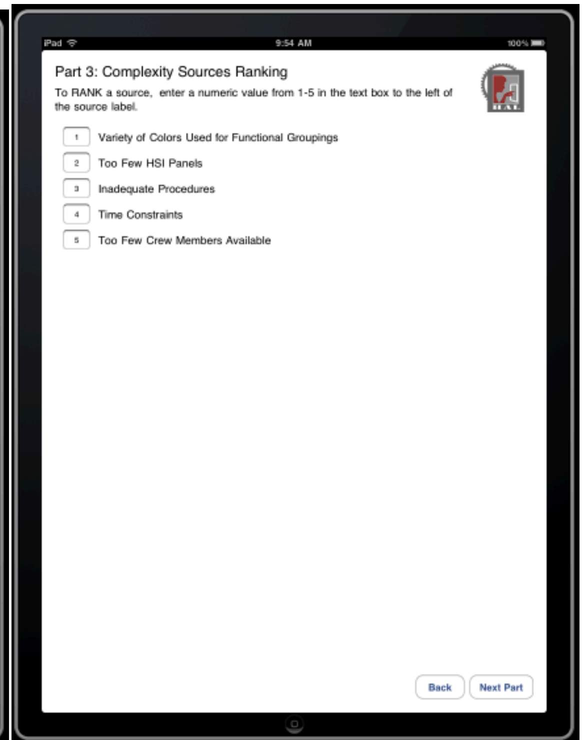

iPad 9:51 AM 100%
Page 9: Human System Interface (Page 3)
The components of the control room with which operators must interact in order to control, monitor, and interact with the system.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
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

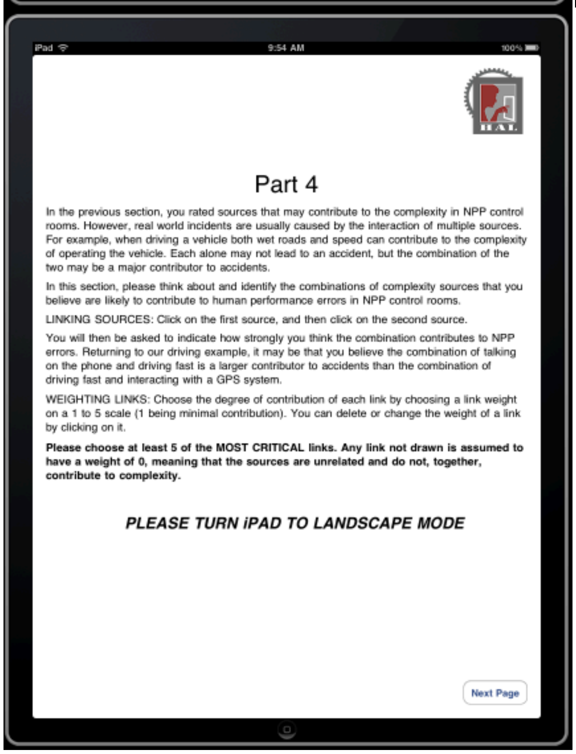

iPad 9:52 AM 100%
Page 10: Cognitive Factors (experience/emotional state)
Those factors unique to individual operators.
This feature contributes to the complexity of a NPP control room:
Strongly Disagree
Disagree
Neither Agree nor Disagree
Agree
Strongly Agree
Inexperience in Current Control Room
Experience in Other Control Rooms
Boredom
Cognitive Fatigue
Stress
N/A 1 2 3 4 5
Previous Page
Next Part

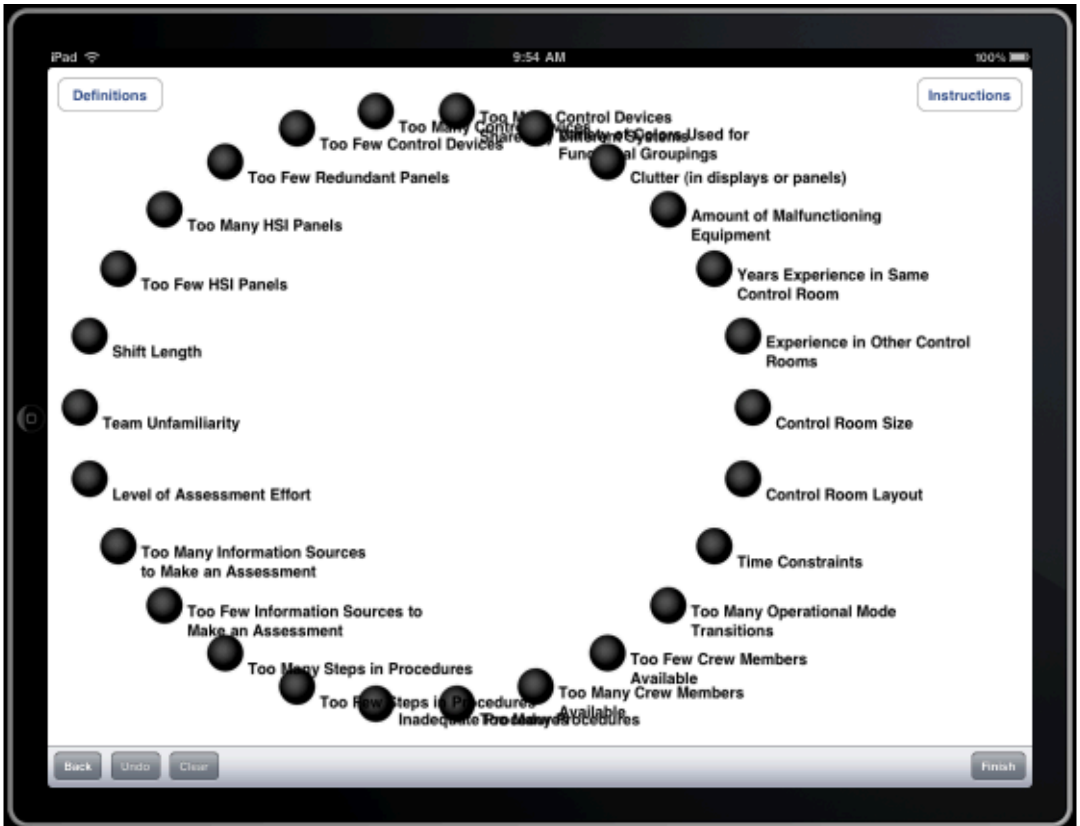

iPad 9:52 AM 100%
Part 3: Complexity Source Ranking
In this part, you will again be presented with the potential sources of complexity. This time, choose the five sources that you believe contribute most to operator performance and rank them from 1-5 (with one being the most significant).
Be sure to 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

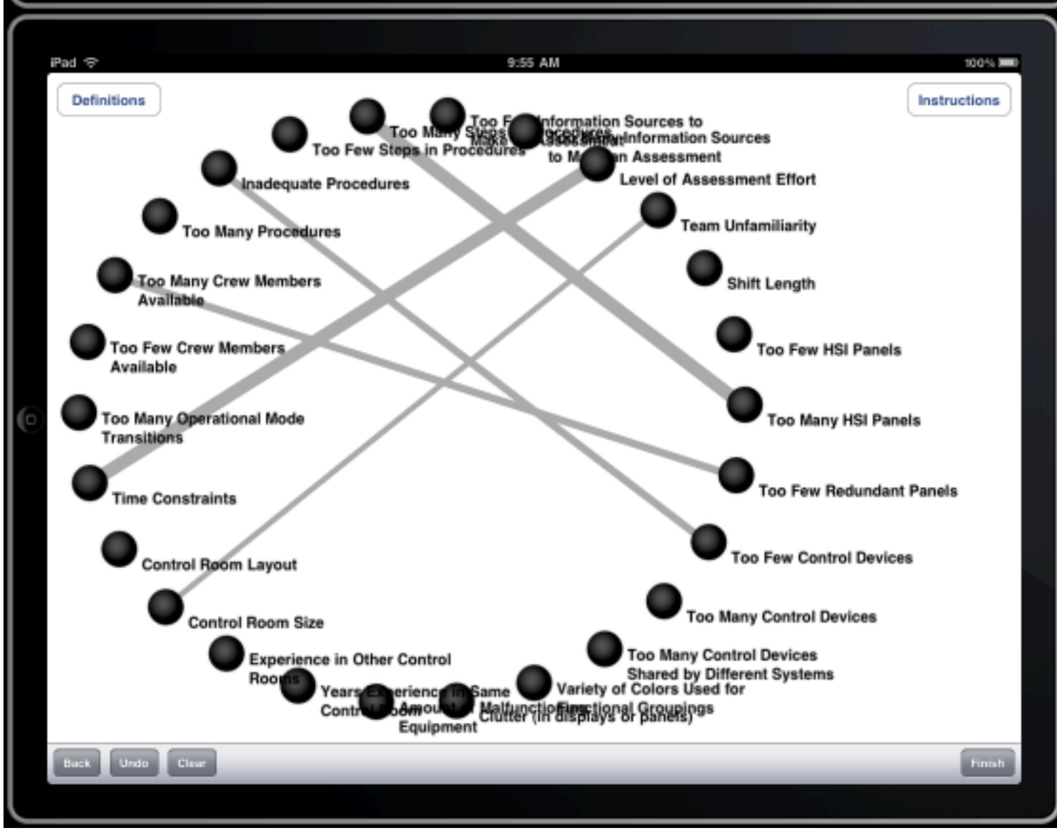

iPad 9:53 AM 100%
Part 3: Complexity Sources Ranking
Label
Select the 5 sources that you feel contribute most to complexity.
Clutter (in displays or panels)
Too Many Operational Mode Transitions
Variety of Colors Used for Functional Groupings
Too Many Steps in Procedures
Too Many Control Devices
Too 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

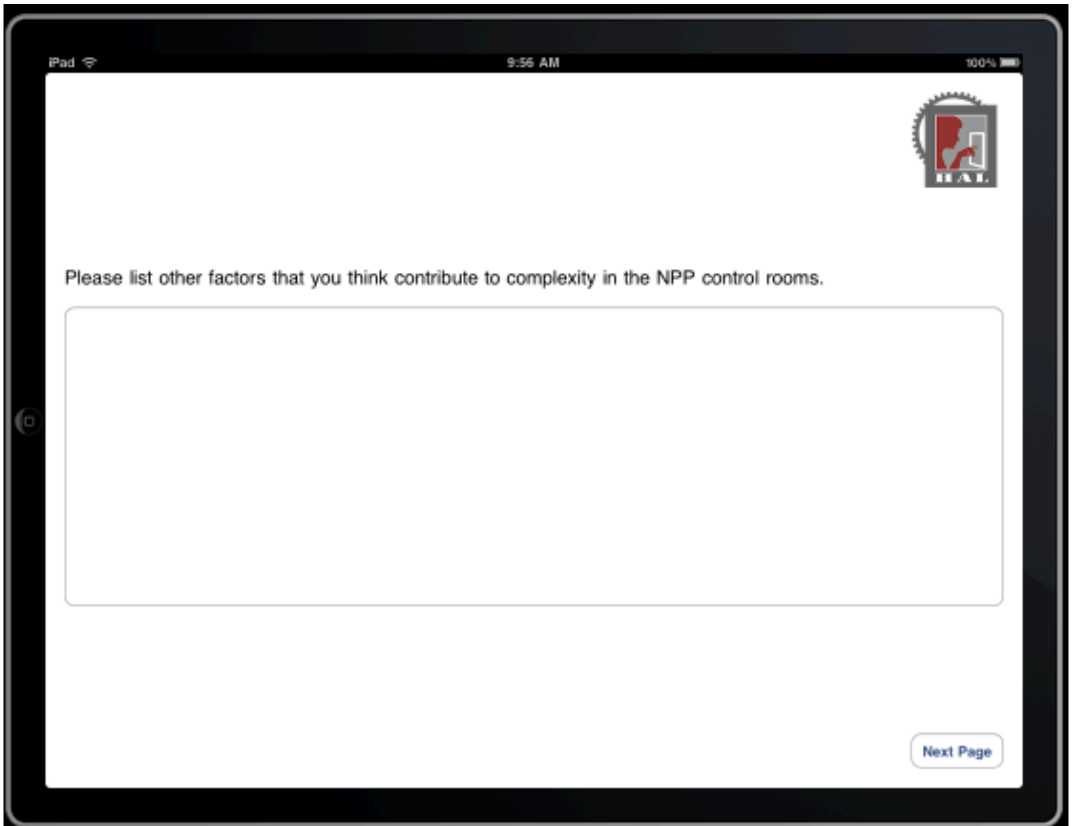

iPad
9:53 AM
100%
Part 3: Complexity Sources Ranking
5
Select the 5 sources that you feel contribute most to complexity.
Clutter (in displays or panels)
Too Many Operational Mode Transitions
Variety of Colors Used for Functional Groupings
Too Many Steps in Procedures
Too Many Control Devices
Too Few 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

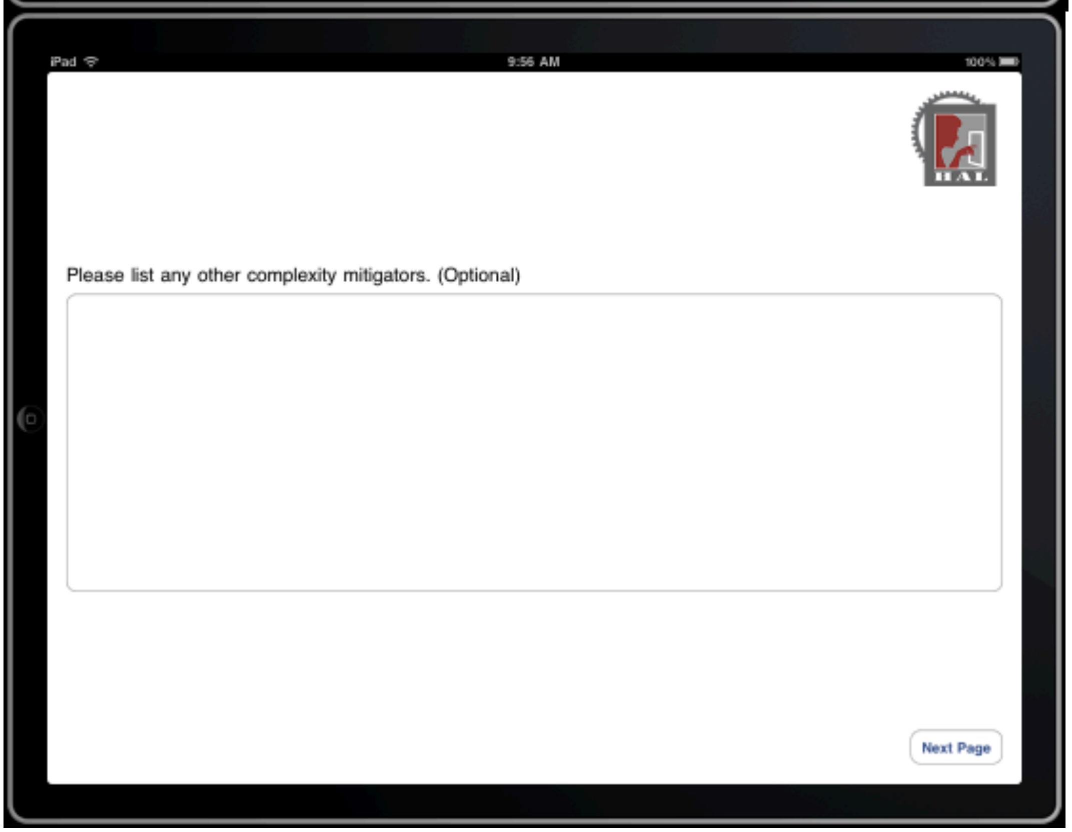

iPad
9:54 AM
100%
Part 3: Complexity Sources Ranking
To RANK a source, enter a numeric value from 1-5 in the text box to the left of the source label.
1 Variety of Colors Used for Functional Groupings
2 Too Few HSI Panels
3 Inadequate Procedures
4 Time Constraints
5 Too Few Crew Members Available
Back
Next Part

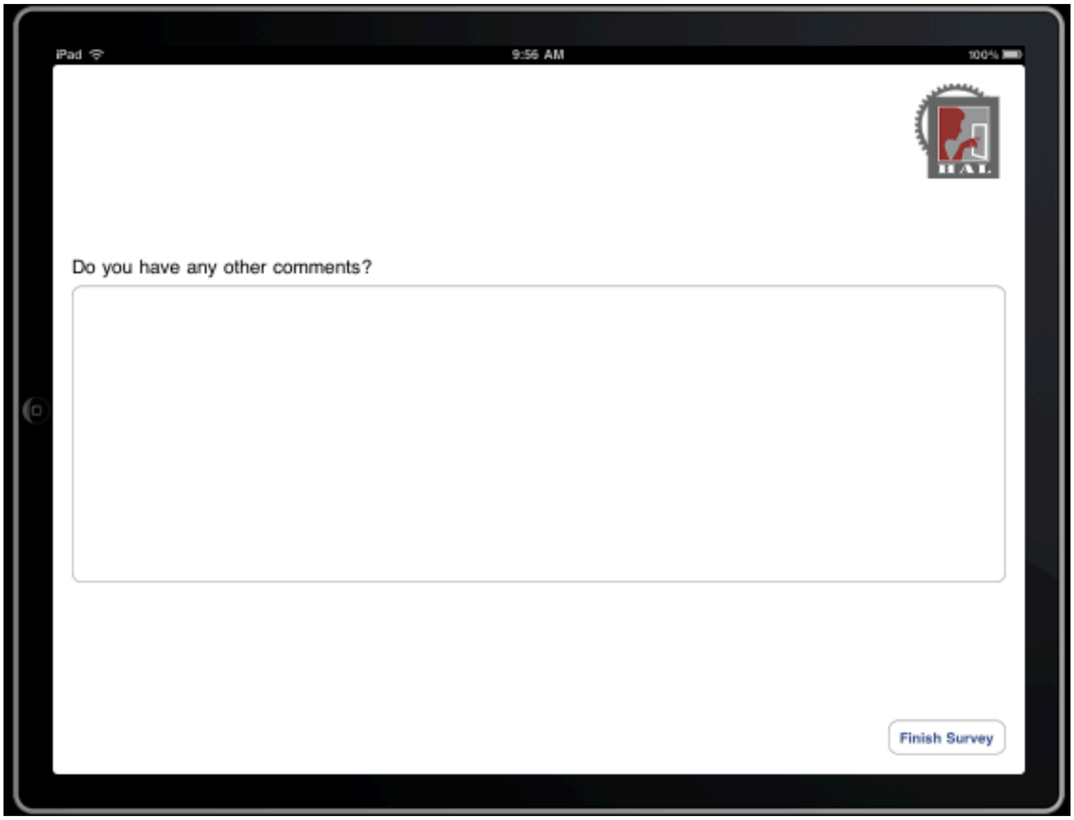

iPad
9:54 AM
100%
Part 4
In the previous section, you rated sources that may contribute to the complexity in NPP control rooms. However, real world incidents are usually caused by the interaction of multiple sources. For example, when driving a vehicle both wet roads and speed can contribute to the complexity 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


iPad
9:54 AM
100%
Definitions
Instructions
Too Few Control Devices
Clutter (in displays or panels)
Too Few Redundant Panels
Amount of Malfunctioning Equipment
Too Many HSI Panels
Years Experience in Same Control Room
Too Few HSI Panels
Experience in Other Control Rooms
Shift Length
Team Unfamiliarity
Control Room Size
Level of Assessment Effort
Control Room Layout
Too Many Information Sources to Make an Assessment
Time Constraints
Too Few Information Sources to Make an Assessment
Too Many Operational Mode Transitions
Too Few Crew Members Available
Too Many Crew Members
Back
Undo
Clear
Finish


iPad
9:55 AM
100%
Definitions
Instructions
Too Few Steps in Procedures
Inadequate Procedures
Level of Assessment Effort
Team Unfamiliarity
Too Many Procedures
Shift Length
Too Many Crew Members Available
Too Few HSI Panels
Too Few Crew Members Available
Too Many HSI Panels
Too Many Operational Mode Transitions
Too Few Redundant Panels
Time Constraints
Too Few Control Devices
Control Room Layout
Too Many Control Devices
Control Room Size
Too Many Control Devices Shared by Different Systems
Experience in Other Control
Variety of Colors Used for
Back
Undo
Clear
Finish


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
100%
Do you have any other comments?
Finish Survey