A NORMAL ACCIDENT THEORY-BASED COMPLEXITY ASSESSMENT METHODOLOGY FOR SAFETY-RELATED EMBEDDED COMPUTER SYSTEMS

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ABSTRACT

A NORMAL ACCIDENT THEORY-BASED COMPLEXITY ASSESSMENT METHODOLOGY FOR SAFETY-RELATED COMPUTER SYSTEMS

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Computer-related accidents have caused injuries and fatalities in numerous applications. Normal Accident Theory (NAT) explains that these accidents are inevitable because of system complexity. Complex systems, such as computer-based systems, are highly interconnected, highly interactive, and tightly coupled. We do not have a scientific methodology to identify and quantify these complexities; specifically, NAT has not been operationalized for computer-based systems.

Our research addressed this by operationalizing NAT for the system requirements of safety-related computer systems. It was theorized that there are two types of system complexity: external and internal. External complexity was characterized by three variables: system predictability, observability, and usability — the dependent variables; internal complexity was characterized by modeling system requirements with Software Cost Reduction dependency graphs, then quantifying model attributes using 15 graph-theoretical metrics — the independent variables. Dependent variable data were obtained by having 32 subjects run simulations of our research test vehicle: the light control system (LCS). The LCS simulation tests used a cross-over design. Subject perceptions of these simulations were obtained by using a questionnaire. Canonical correlation analysis and structure correlations were used to test hypotheses 1 to 3 − the dependent variables predictability, observability, and usability do not correlate with the NAT complexity metrics. Five of 15 metrics proposed for NAT complexity correlated with the dependent data. These 5 metrics had structure correlations exceeding 0.25, standard errors < 0.10, and a 95% confidence interval. Therefore, the null hypotheses were rejected. A Wilcoxon signed ranks test was used to test hypotheses 4 to 6 − increasing NAT complexity increases system predictability, observability, and usability. The results showed that the dependent variables decreased as complexity increased. Therefore, null hypotheses 4 to 6 were rejected. Lastly, this work is a step forward to operationalize NAT for safety-related computer systems; however, limitations exist. Opportunities addressing these limitations and advancing NAT were identified. Lastly, the major contribution of this work is fundamental to scientific research – to gain knowledge through the discovery of relationship between the variables of interest. Specifically, NAT has been advanced by defining and quantifying complexity measures, and showing their inverse relationship to system predictability, observability, and usability.

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An accomplishment needs growth − personal growth in terms of learning about ourselves, how we think and learn, and how we view ourselves in relation to our friends, family, and our profession − intellectual growth in terms of learning new methods and techniques in our discipline and other disciplines, and by meeting the intellectual challenges we face when making a contribution of new knowledge.

There is a process to realize our accomplishment: we have a dream, we recognize and grasp an opportunity, we have and maintain a desire, we take action, and most importantly, we receive the support, understanding, and encouragement of family, friends, and colleagues.

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CHAPTER 1
INTRODUCTION AND BACKGROUND

This section introduces the research motivation and presents an overview of the general problem area. It describes the research significance and gives an overview of the research including the scope and limitations. Background information follows to establish fundamental concepts and a common understanding of terms.

Motivation

There is an increasing trend of embedding computer technology into a wide variety of systems because this technology enables systems to provide new functionality, made possible only by computer control, to improve efficiency and to make the systems more cost competitive. Thus, traditional hardwired electro-mechanical and analog systems are often replaced with computer hardware and software. This widespread use increases our dependence on and exposure to computer-based systems. More importantly, it impacts our safety because complex computer-based systems have inherent hazards.

For example, computer-related accidents have caused mission failures, harm to the environment, injuries, and fatalities in numerous applications. Over 400 computer-related accidents, up to 1995, were documented (Neumann, 1995); it was estimated in 1994 that about 2000 deaths were computer-related (MacKenzie, 1994).

Systems utilizing computer technology are more complex. As a result, new hazards are created that are difficult to recognize or mitigate with existing safety techniques. This trend of utilizing computer technology will continue, due to global market pressures and our quest for "improved" systems providing more and new functionality. The following examples represent the spectrum endpoints of "high-tech" and "low-tech" systems.

Hi-tech military weapon systems employ sophisticated computer technologies to provide unparalleled functionality. The dependence on software to provide functionality is drastically increasing. As early as 1981, 80 percent of US weapon systems employed computer technology (Leveson, 1986). In 1960 the F-4 weapon system had only eight percent of its functions performed by software. In 2000, the F-22 weapon system had an estimated 80 percent of its functions in software (Nelson, Clark, & Spurlock, 1999).

Mining has traditionally been low tech; however, in recent years, people have begun using complex computerized mining systems. As stated in the Wall Street Journal (Philips, March 18, 1997) "Mining, that most basic of industries, is increasingly throwing down its old tools and picking up new technology. It's a matter of survival." A recent survey shows that over 95 percent of all longwall mining systems are computer based (Fiscor, 1998). Computer technology is embedded in diverse mining systems including “driver-less” underground and surface haulage vehicles, continuous mining machines, hoists and elevators, and mine atmospheric monitoring systems.

Complexity Hazards

As computer utilization proliferates, escalating levels of system sophistication and complexity increase the likelihood of design errors and the introduction of new hazards. Noted researchers support this problem statement. Littlewood (Littlewood & Strigini, 1992) stated: “The problems essentially arise from complexity, which increases the possibility that design faults will persist and emerge in the final product.”

Leveson expands upon the consequences of computer-induced system complexity:

> Many of the new hazards are related to increased complexity (both product and process) in the systems we are building. Not only are new hazards created by the complexity, but the complexity makes identifying them more difficult (Leveson, 1995).

> Computers are introducing new types of failure modes that cannot be handled by traditional approaches to designing for reliability and safety (such as redundancy) and by standard analysis techniques (such as FMEA). These techniques work best for failures caused by random, wear-out phenomena and for accidents arising in the individual system components rather than in their interactions (Leveson, 2000).

Today, systems embedded with computer technology are extremely complex. New failure modes are resulting from complex interactions between components and subsystems. For instance, mining is an industry sector experiencing a new complexity-related hazard informally named ghosting: the unexpected movement or startup of a mining system. From 1995 to 2001, 11 computer-related mining incidents in the U.S. were reported by the Mine Safety and Health Administration; 71 computer-related mining incidents were reported in Australia (Sammarco, 2003). The National Institute for Occupational Safety and Health (NIOSH) has recognized the hazards associated with complexity and is funding this research to develop a complexity assessment methodology that enables the realization of simpler, safer computer-based systems (Sammarco, 2002).

Normal Accident Theory and Complexity

Perrow theorizes that accidents are inevitable with complex, tightly coupled systems because the complexity enables *unexpected interactions* that lead to system accidents (Perrow, 1999). System designers are not able to understand or anticipate these interactions, nor are the end-users able to recognize, understand, or correctly intervene to stop or correct them. Perrow's theory, named Normal Accident Theory (NAT), has much support (Ladkin, 1996) (Leveson, 2000) (Mellor, 1994) (Rushby, 1994) (Wolf, 2000), yet only Wolf has operationalized the theory. Wolf's work is specialized for petroleum processing plants.

NAT has not been operationalized for the safety-critical embedded computer system domain. Operationalization involves quantification of empirical attributes or indicators by measurement or assignment of numbers and scales. It also includes the translation of informal definitions to observable operations and processes.

Research Hypotheses

We theorized there are two types of system complexity. The first type is internal; this is the complexity of a system's structure and design. The second type is external; this complexity is apparent in the externally visible behavior of a system. Specifically, a complex system can have unfamiliar, unplanned, or unexpected behaviors as viewed by the human interacting with the system. The human perceives system behavior as unpredictable. Also, these behaviors could be difficult to observe and not immediately comprehensible by the end-user (Perrow, 1999). As a result, the system's usability can decline. Hence, system complexity can be indicated by an external component: system behavior we characterized system behavior with three variables: system predictability, observability, and usability. These were the dependent variables for our research. The NAT complexity metrics of internal complexity are the independent variables.

Hence, we hypothesized a negative correlation exists between NAT complexity, as measured by graph-theoretical metrics, and the externally visible behavior of a system. Six research hypotheses are presented.

Hypothesis 1:

H_0: There is not a correlation between NAT metrics and system predictability.

H_1: NAT metrics are correlated to system predictability.

Hypothesis 2:

H_0: There is not a correlation between NAT metrics and system observability.

H_1: NAT metrics are correlated to system observability.

Hypothesis 3:

H_0: There is not a correlation between NAT metrics and system usability.

H_1: NAT metrics are correlated to system usability.

Hypothesis 4:

H_0: Increasing interactive complexity does not decrease system predictability.

H_1: Increasing interactive complexity decreases system predictability.

Hypothesis 5:

H_0: Increasing interactive complexity does not decrease system observability.

H_1: Increasing interactive complexity decreases system observability.

Hypothesis 6:

H_0: Increasing interactive complexity does not decrease system usability.

H_1: Increasing interactive complexity decreases system usability.

Research Significance

This research is the first to operationalize NAT for safety-critical embedded computer systems. It develops a methodology for early identification and quantification of complexity at the system level. Figure 1-1 depicts the research importance.

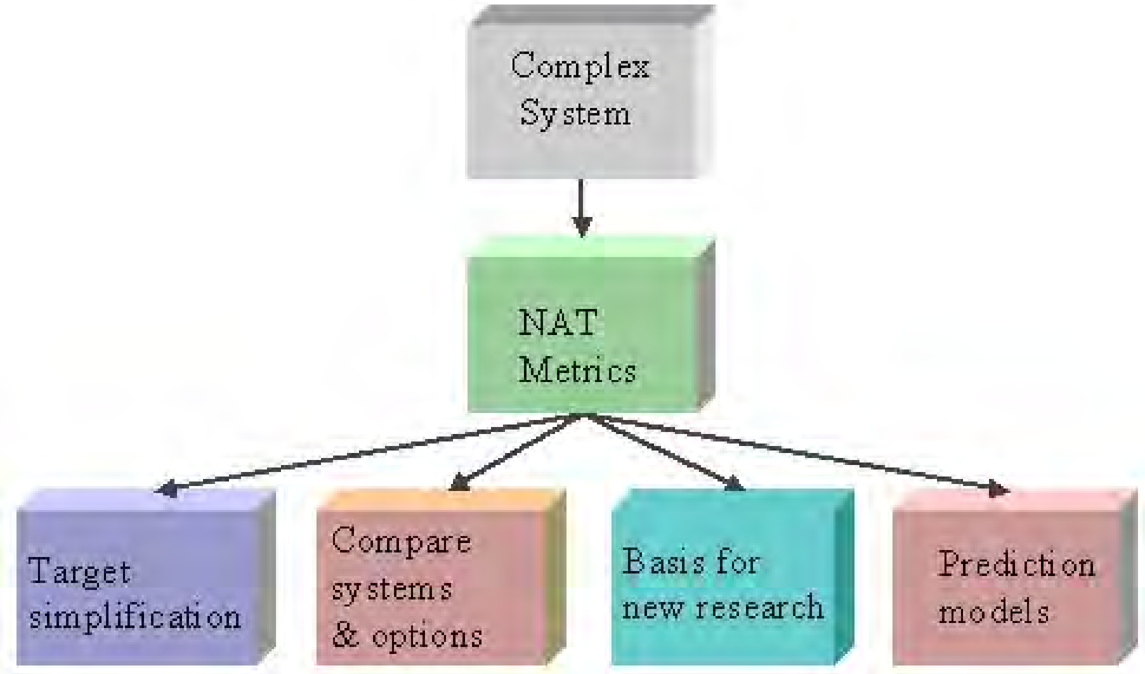

Figure 1-1. The broadly defined research importance.

Scope

The scope of this dissertation is limited to the life cycle stage of requirements, because most errors occur at these stages (Davis, 1993) (Lutz, 1996); errors are much less costly to correct early rather than later (Davis, 1993) (Nelson et al., 1999); requirement errors propagate to cause errors in later life cycle phases (Kelly, Sherif, & Hops, 1992).

Dissertation Structure

Chapter 2 presents the research objective of developing a complexity assessment methodology for system level requirements of safety-related computer systems. The specific aims to realize this objective are also presented. Chapter 3 contains a literature survey of related work in the areas of NAT and complexity metrics. Chapter 4 addresses the modeling of system requirements. Criteria are established for selecting a modeling method that is appropriate for safety-related computer systems, and that enable measurement of the desired NAT attributes. Based on these criteria, the Software Cost Reduction (SCR) method was selected for modeling system requirements. The SCR method and associated tool set are described. Chapter 5 presents the complexity metrics for NAT as applied in the context of safety-related computer systems. Chapter 6 describes the research vehicle: the Light Control System (LCS), devised by the Fraunhofer Institute for Experimental Software Engineering in Germany. The LCS was used as a case study to compare different approaches for requirements elicitation and specification. Chapter 7 presents the research methodology, which uses a cross-over design in combination with the Discount Usability Engineering method. This chapter also describes tests involving Human subjects. They ran numerous PC-based system simulations of the LCS. The data we collected enabled us to measure three dimensions of system complexity from the user's perspective. Chapter 8 presents the results of these tests as well as, the statistical testing of the six research hypotheses. Chapter 9 discusses our interpretations of the data and our statistical test results. Finally, Chapter 10 provides a research summary and discusses three primary conclusions.

Background

This section contains relevant background information to orient the reader, provide a foundation of basic safety concepts, clarify commonly misunderstood system safety concepts, and define key terms used in this dissertation.

Safety and Reliability

Often, safety and reliability are incorrectly equated in the sense that if a system is reliable, then it is safe. Reliability alone is not sufficient for safety. For example, a reliable system may have unsafe functions and conditions, or neglect to provide all safety functions. The result is a reliably unsafe system!

Safety is "freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment" (DoD, 1997) while reliability is "the probability that a piece of equipment or component [of a system] will perform its intended function satisfactorily for a prescribed time and under stipulated environmental conditions"(Leveson, 1995), pg 172. Thus, a system could be reliable but unsafe, or a system could be safe but unreliable.

What is a System?

One of the first steps of a safety analysis is to define the system. A conceptual view of a system is represented by the SHEL model: a simple system model comprised of (S)oftware, (H)ardware, (E)nvironment and (L)iveware or humans as depicted by Figure 1-2 (Hawkins, 1993). This system abstraction is employed by this dissertation.

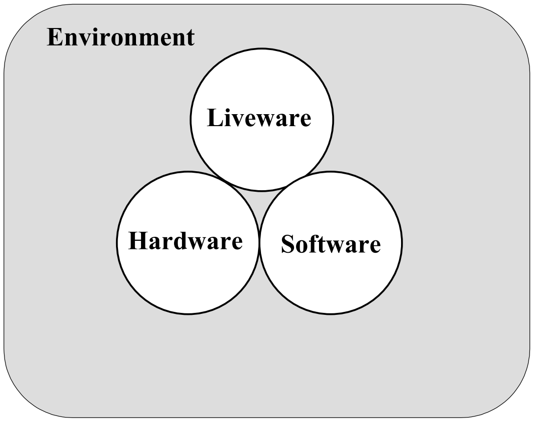

Figure 1-2. The SHEL conceptual model of a system.

Safety must be from a system viewpoint. Safety cannot be assured if efforts are focused only on part of the system because *safety is an emergent property of the entire system*. Safety emerges once all subsystems have been integrated. For example, the software can be totally free of "bugs" and employ numerous safety features, yet the system can be unsafe because of how the software interacts and operates with the other parts of the system. In other words, the sum may not be as safe as the individual parts.

The System Safety Approach

System safety, as defined by the military standard MIL-STD 882D, is "the application of engineering and management principles, criteria and techniques to achieve acceptable risk, within the constraints of operational effectiveness, time and cost throughout all phases of the system life cycle" (DoD, 1997). System safety received much scientific attention during and after World War II. This was the time when most of our traditional safety techniques were developed to address new challenges posed by systems that were more complex due to the use of new technology (Leveson, 1995). The traditional "fly-fix-fly" approach to safety did not work well with these complex systems. It was too dangerous, costly and wasteful to continue with this "after-the-fact approach", so the system safety concept was initiated as a "before-the- fact" process (Roland & Moriarity, 1982). The key concepts are listed:

1) Integrating safety into the design
2) Systematic hazard identification and analysis
3) Addressing the entire system in addition to the subsystems and components
4) Using qualitative and quantitative approaches

The system safety process is documented in MIL-STD-882, the most widely known safety standard. Existing safety standards are built upon collections of expertise and experiences (lessons learned) involving fatalities, injuries and near misses. In general, standards also provide uniform, systematic approaches. History has shown that standards are effective tools for safety (Leveson, 1992). Many safety standards have been created. The Software Verification Centre of the University of Queensland in Australia has compiled an international survey of safety standards (Wabenhorst & Atchison, 1999). Hermann (Herrmann, 1999) presents detailed information concerning standards of key industrial sectors.

Hazard Analysis

Hazard analysis is a key component of the system safety approach. A hazard is "any real or potential condition that can cause injury, illness, or death to personnel or damage to or loss of equipment or property, or damage to environment" (DoD, 1997).

Many techniques, ranging from simple qualitative methods to advanced quantitative methods, are available to help identify and analyze hazards. The System Safety Analysis Handbook (System Safety Society, 1997) provides extensive listings and descriptions. Some examples of the more commonly used techniques are the Preliminary Hazard List (PHL), Preliminary Hazard Analysis (PHA), Hazard and Operability Study (HAZOP) and Failure Modes and Effects Analysis (FMEA). The use of multiple hazard analysis techniques is recommended because each has its own purpose, strengths and weaknesses. Typically, each technique addresses certain aspects of safety; thus, one technique alone is not sufficient to identify and analyze all hazards of a system.

To be effective, the hazard analysis process must be applied over the life cycle of the system in a continual and iterative manner. That is, hazard identification and analysis must start at the conceptual stage of the system life cycle, when there are easier and less costly to address. Hazard analysis continues on through the definition, development, production, and deployment stages. The systematic approach to safety is captured in the *safety life cycle*. It enables safety to be "designed in" early rather than being addressed after the system's design is completed.

The Safety Life Cycle

The use of a safety life cycle is required to ensure that safety is applied in a systematic manner, thus reducing the potential for design errors. The safety life cycle concept is applied during the entire life of the system. Hazards can become evident at later stages or new hazards can be introduced by system modifications. Figure 1-3 depicts the safety life cycle phases (International Electrotechnical Commission (IEC), 1997).

The safety life cycle must be integrated within the overall product development life cycle because safety issues impact overall development issues and vice versa. Secondly, an integrated approach minimizes the likelihood of addressing safety as an afterthought of the system design. An example merging the safety life cycle of Figure 1-3 with the development life cycle is shown in Figure 1-4.

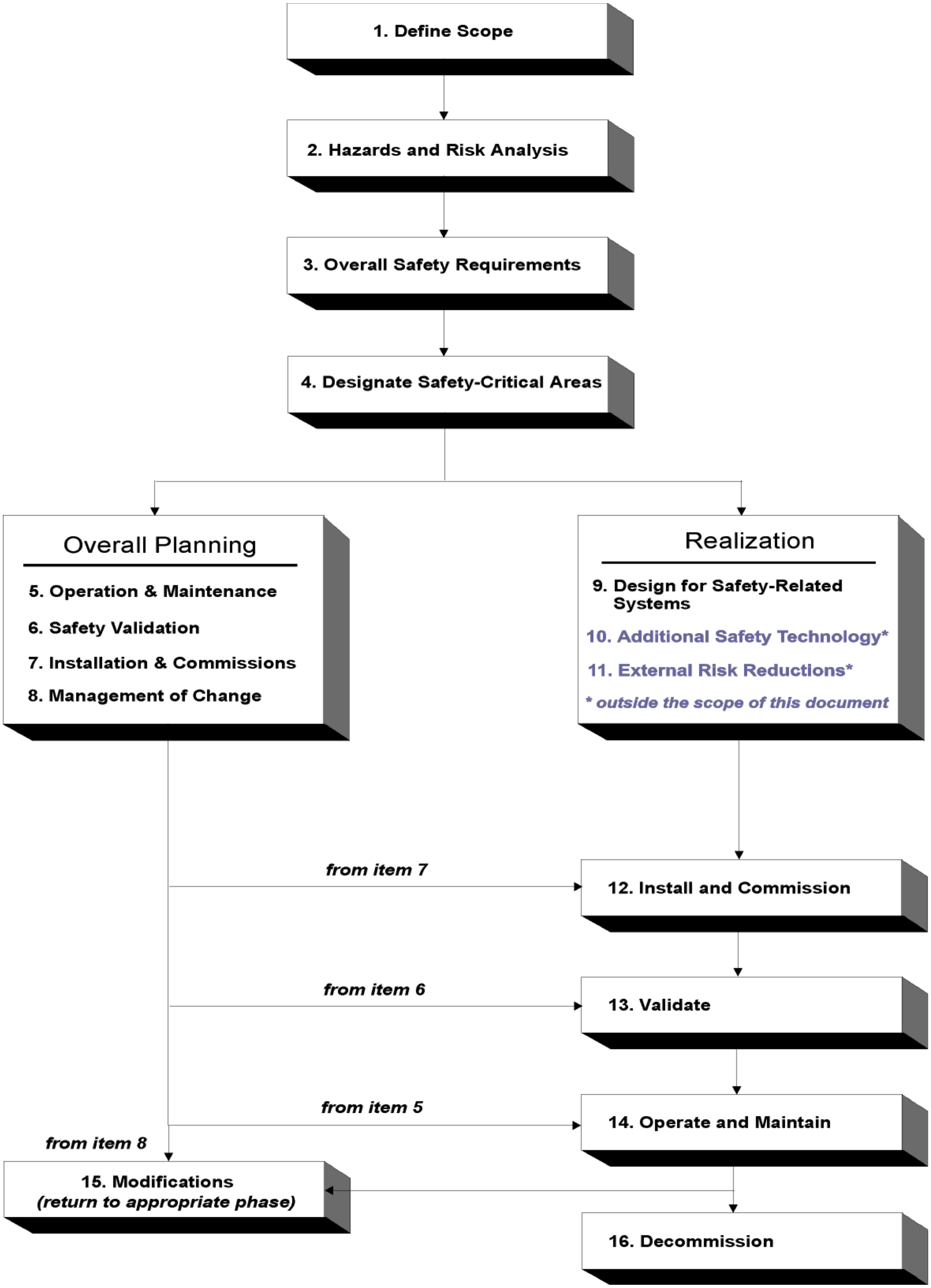
1. Define Scope
2. Hazards and Risk Analysis
3. Overall Safety Requirements
4. Designate Safety-Critical Areas
Overall Planning
5. Operation & Maintenance
6. Safety Validation
7. Installation & Commissions
8. Management of Change
Realization
9. Design for Safety-Related Systems
10. Additional Safety Technology*
11. External Risk Reductions*
* outside the scope of this document
from item 7
12. Install and Commission
from item 6
13. Validate
from item 5
14. Operate and Maintain
from item 8
15. Modifications
(return to appropriate phase)
16. Decommission

Figure 1-3. The safety life cycle (International Electrotechnical Commission, 1997).

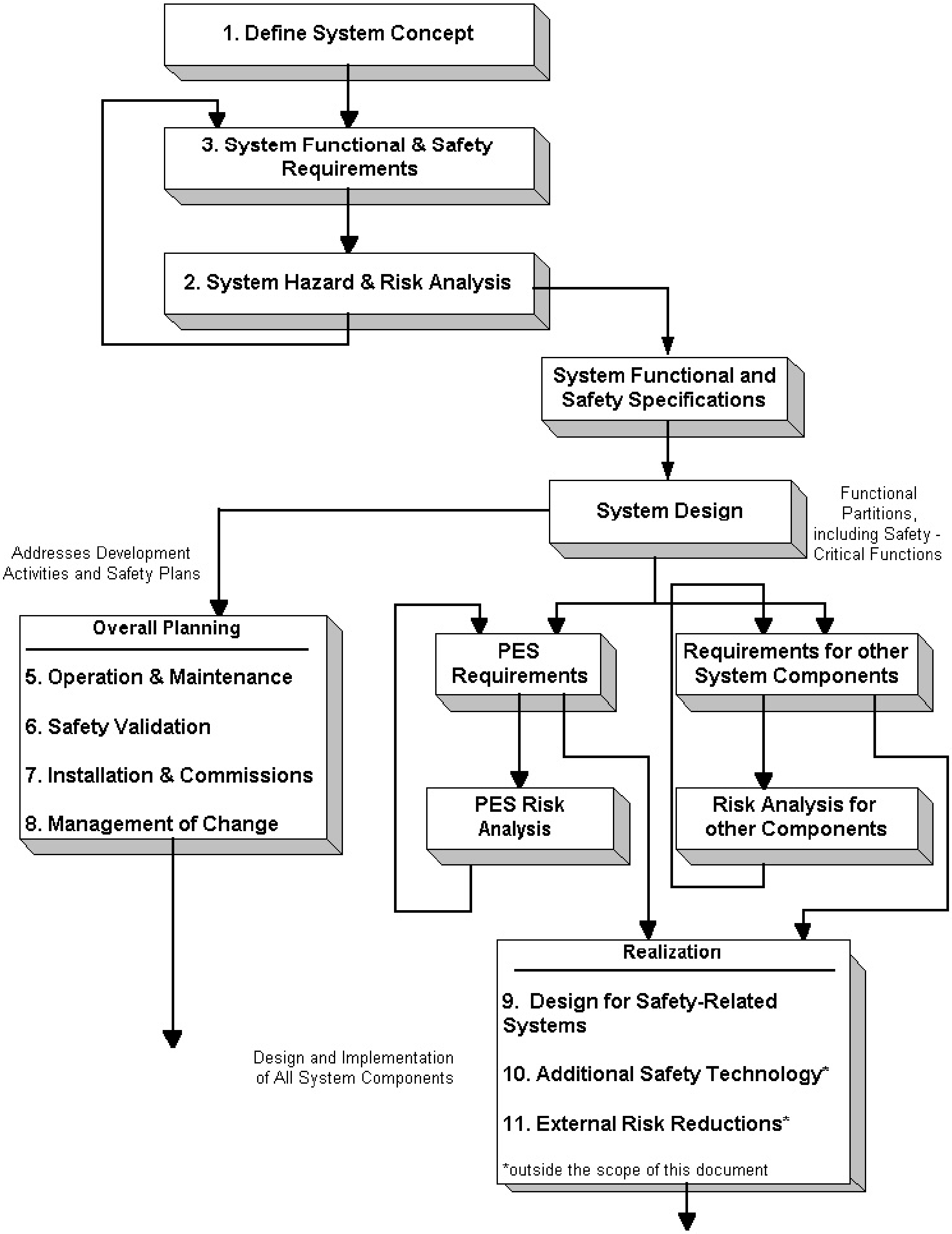
1. Define System Concept
3. System Functional & Safety Requirements
2. System Hazard & Risk Analysis
System Functional and Safety Specifications
System Design
Functional Partitions, including Safety - Critical Functions
Addresses Development Activities and Safety Plans
Overall Planning
5. Operation & Maintenance
6. Safety Validation
7. Installation & Commissions
8. Management of Change
PES Requirements
Requirements for other System Components
PES Risk Analysis
Risk Analysis for other Components
Realization
9. Design for Safety-Related Systems
10. Additional Safety Technology*
11. External Risk Reductions*
*outside the scope of this document
Design and Implementation of All System Components

Figure 1-4. A merged safety and development life cycle (Sammarco & Fisher, 2001).
Note: PES is a programmable electronic system

Faults, Errors, and Failures

There is confusion concerning faults, errors and failures; often the terms are used interchangeably. Figure 1-5 depicts the relationship between a fault, error, and failure.

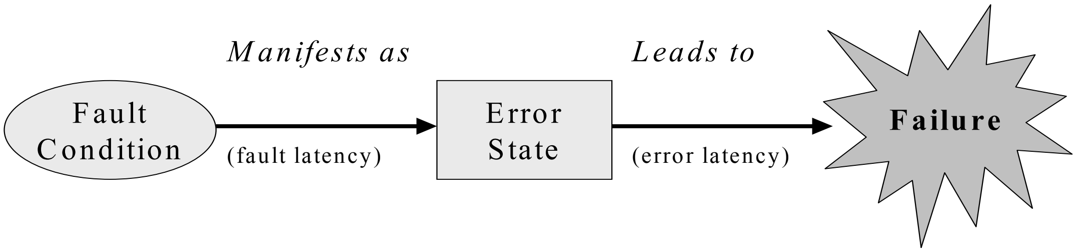

Figure 1-5. Fault, Error, and Failure Relationship.

A failure is "the termination of the ability of a functional unit to perform a required function"(International Electrotechnical Commission (IEC), 1998). This definition is based on a performance of a function, so *failure is a behavior* occurring at an instant in time. A fault is an abnormal condition. Faults are random (hardware) or systematic (hardware or software). Random faults are due to physical wear-out, degradation, or defects; random faults can be accurately predicted and quantified. Systematic faults concern the specification, design, and implementation. Software faults are systematic. Faults, both random and systematic, may lead to errors (Storey, 1996).

An error is a system state that potentially can lead to a failure. When a fault results in an error, the error is then a manifestation of the fault and the fault becomes apparent. Not all faults lead to errors or failures. Some faults are benign or are tolerated such that failure does not occur. Some faults are dormant such that an error state or failure does not occur because the proper conditions do not exist. For example, a fault could reside in a section of software. If that section of software is not used, then neither an error state nor failure will occur.

How Does Software Contribute to Complexity?

Software is especially prone to complexity because it can be non-deterministic, contain numerous branches and interrupts, contain temporal criticality and consist of hundreds of thousands of lines of code. Software does not exhibit random wear out failures. Instead, software failures result from logic or design errors.

Beizer (Beizer, 1990) gives an example illustrating an aspect of software complexity concerning the number of paths for a section of code. Given that a section of software has 2 loops, 4 branches and 8 states, Beizer calculates the number of paths through this code to exceed 8000!

Complexity and Safety

Simplification is one of the most important design aspects for safety. Complexity makes it more difficult to conceptualize, understand, specify, design, test, document, maintain, modify, and review the system. Complexity also makes it more likely for errors, failure, and unplanned interactions to occur that may cause unsafe conditions. It also increases demands on humans to operate and maintain the system. As a result, humans can unknowingly put the system in an unsafe state during operation or maintenance.

Definitions

Complexity: a) having many varied interrelated parts, patterns, or elements and consequently hard to understand fully; b) marked by an involvement of many parts, aspects, details, notions and necessitating earnest study or examination to understand or cope with (Gove, 1996).

Coupling: A measure of the strength of the interconnectedness between system components.

Error: A discrepancy between a computed, observed or measured value or condition and the true, specified or theoretically correct value or condition (International Electrotechnical Commission (IEC), 1998).

Failure: The termination of the ability of a functional unit to perform a required function (International Electrotechnical Commission (IEC), 1998).

Fault: An abnormal condition that may cause a reduction in, or loss of, the capability of a functional unit to perform a required function (International Electrotechnical Commission (IEC), 1998).

Hazard: Any real or potential condition that can cause injury, illness, or death to personnel or damage to or loss of equipment or property, or damage to environment (Reason, 1999).

Interactive complexity: Complex interactions are those of unfamiliar sequences, or unplanned and unexpected sequences and either not visible or immediately comprehensible (Perrow, 1999).

Measure: A mapping from a set of entities and attributes in the real world to a representation or model in the mathematical world (Fenton & Pfleeger, 1997).

Mistake (Human error): A human action or inaction that produces an unintended result (International Electrotechnical Commission (IEC), 1998).

Probabilistic risk assessment (PRA): A systematic method that includes risk analysis and the derivation of risk profiles in order to quantify the outcomes and their probability or likelihood (Kumamoto & Henley, 1996).

Reliability: Probability that failure time T is greater than operating time *t* ((Siewiorek, 1998).

$$R(t) = P(T>t) \quad \textbf{(1-1)}$$

or

$$R(t) = e^{-\lambda t} \quad \textbf{(1-2)}$$

for an exponential probability distribution

where λ = failures / (time or natural units)

Risk: The combination of the probability of occurrence of harm and the severity of that harm (International Electrotechnical Commission (IEC), 1998).

Risk assessment: Assessment of the system or component to establish that the achieved risk level is lower than or equal to the tolerable risk level (Welch, 1998).

Safety: Freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property, or damage to the environment (Reason, 1999).

Safety-critical: A term that describes any condition, event, operation, process or item of whose proper recognition, control, performance or tolerance is essential to safe system operation or use; e.g., safety-critical function, safety-critical path, safety-critical component (Reason, 1999).

Software Error: An incorrect step, process, or data definition; for example, an incorrect instruction in a computer program.

Software Failure: An event in which a system or system component does not perform a required function within specified limits (Welch, 1998).

Software Fault: A manifestation of an error in the software. If encountered, a failure *might* result (Welch, 1998).

Software Reliability: The probability that software will not cause the failure of a system for a specified time under specified conditions. The probability is a function of the inputs to and use of, the system as well as a function of the existence of faults in the software. The inputs to the system determine whether existing faults, if any, are encountered (Welch, 1998).

Subsystem: An element of the system that itself may be a system (Reason, 1999).

System: A collection of hardware, software, humans and machines *interconnected* to perform desired functions.

System accident: The unintended interaction of multiple failures in a tightly coupled system that allows cascading of the failures beyond the original failures (Perrow, 1999).

System reliability: The probability that a *system*, including all hardware and software subsystems, will perform a required task or mission for a specified time in a specified operational environment (Welch, 1998).

System safety: The application of engineering and management principles, criteria and techniques to achieve acceptable risk, within the constraints of operational effectiveness, time and cost throughout all phases of the system life cycle (Reason, 1999).

Summary

Escalating computer technology utilization is resulting in complex systems containing new types of hazards having the potential to result in accidents. The complexity of these systems makes it more likely for errors, failure and unplanned interactions that can cause accidents. The generalized problem is that the nature of accidents has changed for complex, computer-controlled systems; however, our assessment methods have remained unchanged since their inception during World War II; thus, another approach as needed. Our research is a first step to address this need by developing a methodology to assess and quantify NAT complexity at the system level.

Finally, relevant background information was presented to provided a foundation of basic safety concepts, clarify commonly misunderstood relationships, and introduce terminology in order to provide a common understanding and enable effective communication.

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CHAPTER 2
RESEARCH OBJECTIVE AND SPECIFIC AIMS

Our ability to understand and manage the complexities of computer-based systems has not kept pace with the technology's utilization. We are ill-equipped because a scientific methodology does not exist to identify and quantify the most important attributes of complexity that impact the safety of these systems. As a result, computer-related accidents causing mission failures, harm to the environment, injuries, and fatalities have occurred. Neumann (Neumann, 1995) documented over 400 computer-related accidents and MacKenzie determined that about 2000 deaths were computer-related (MacKenzie, 1994).

Accidents resulting from system complexity are explained by Normal Accident Theory (NAT). This theory has much support (Leveson, 2000; Mellor, 1994; Rushby, 1994; Sagan, 1993); however, only Wolf has operationalized NAT. His research (Wolf 2000) is specific to petroleum refining processes.

Our research is a first step that operationalizes NAT for the requirements phase. It is a step that transfers theory to practice by establishing concrete, quantifiable system-level complexity metrics so that complexities impacting safety can be identified and reduced before they are propagated to other development phases. The ability to quantify complexity is extremely important. As Lord Kelvin stated:

> When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind: it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced it to the stage of understanding (William Thomson (Lord Kelvin), 1889).

Research Objective

To develop a complexity assessment methodology for system requirements of safety-related computer systems by operationalizing Normal Accident Theory (NAT).

Specific Aims

1. Identify the NAT attributes to operationalize with respect to system requirements.

2. Identify a formal modeling method for system requirements that will afford quantification of the potential metrics.

3. Identify potential metrics for each NAT attribute to be operationalized. At least one metric, and ideally four metrics, should be identified for each of these NAT attributes.

4. Determine which, if any of the potential metrics are useful measures or indicators of NAT complexity.

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CHAPTER 3
LITERATURE REVIEW

This chapter discusses previous work in Normal Accident Theory (NAT) and complexity metrics, critiques the limitations and inadequacies of this research, and draws distinctions between prior work and the proposed research.

Normal Accident Theory

Perrow, an organizational theorist, is the originator of NAT. His work began in 1979 when he was advising a presidential commission investigating the accident at Three Mile Island. Basically, Perrow identified system complexity as the primary accident cause and identified system complexity attributes. A system accident, as defined by Perrow, involves the unintended interaction of multiple failures in a tightly coupled system that allows a cascading of failures. He concluded that these accident types were built-in or inevitable with complex, high technological systems; Perrow stated these accidents were a “normal” occurrence because of complexity; hence, the theory was named Normal Accident Theory. This theory identifies two important system characteristics, tight coupling and interactive complexity, make complex software driven systems especially prone to system accidents (Perrow, 1999). Tables 3-1 and 3-2, respectively, list the system attributes for interactive complexity and tight coupling. Interactively complex systems have the potential to generate many nonlinear branching paths among subsystems. These interactions can be unexpected, unplanned, incomprehensible, and unperceivable to system designers or system users. Therefore, abnormal outcomes are more likely and human interventions are less likely to mitigate the abnormal outcomes.

Coupling is a measure of the strength of the interconnectedness between system components. Tightly coupled systems have little or no slack; thus, they rapidly respond to and propagate perturbations such that operators do not have the time or ability to determine what is wrong. As a result, human intervention is unlikely or improper.

Table 3-1. Tight Coupling Attributes

Tight Coupling Attributes	Comments
Time-dependency	Less tolerant of delays
Sequences	Invariant sequences
Flexibility	Equifinality or limited ways to reach the goal or implement a function
Slack	Little or no slack in system structure or behavior
Substitutions	Limited substitutions of system components, units, or subsystems.

Table 3-2. Interactive Complexity Attributes

Complex System Attributes	Comments
Proximity	Close proximity of physical components or process steps, less underutilized space
Common-mode connections	Many common-mode connections
Interconnected subsystems	Many interconnections
Substitutions	Limited substitutions of people, hardware, or software; exacting requirements
Feedback loops	Unfamiliar or unintended feedback loops
Control parameters	Multiple and interacting control parameters
Information quality	Indirect, inferential, or incomplete information
Understanding of system structure and behavior	Limited, incomplete, or incorrect understanding.

Normal Accident Theory Limitations

Perrow’s complexity theory has made inroads with notable computer science researchers (Leveson, 1995; Ladkin, 1996) although it is based in organizational theory. However, there are opportunities to refine and extend Perrow's work. These opportunities address the needs for complexity quantification, consideration of multiple perspectives, and rigorous scientific validation. Also, Perrow acknowledges that the theory has not been extended to computer technology. He states, "The metaphor of an accident residing in the complexity and coupling of the system itself, not in the failures of its components has seeped into many areas where I never thought to apply it. I have listed these in Figure A.1 . . ." (Perrow, 1999; pg 354). His figure lists software as a neglected or new area to consider.

Quantification

Hopkins (Hopkins, 1999) cites "ill-defined concepts" and "the absence of criteria for measuring complexity and coupling" as significant limitations. Kates notes the same limitations and stated, "the absence of clear criteria for measuring complexity and coupling makes his [Perrow's] examples seem anecdotal, inconsistent, and subjective (Kates, 1986). Quantitative measures of interactive complexity and coupling would address these limitations and could serve to promote the theory.

Linear and complex systems

Perrow uses linear systems as a contrast to complex systems. The opposite of a complex system is a simple system. Simplification is very important for eliminating or reducing hazards. Leveson supports this by writing: "One of the most important aspects of safe design is simplicity. A simple design tends to minimize the number of parts, functional modes, and interfaces, and it has a small number of unknowns in terms of interactions with the system and with system operation." (Leveson, 1995; pg 405).

Multiple perspectives

NAT does not address multiple projections (perspectives). Complexity is multidimensional so, incorporating multiple projections could give added insight to the complexity problem.

The perspectives of the system designers and users are important. For example, consider a system with two operational modes, automatic and manual. The user switches the system from the automatic mode to manual mode to clear "jammed" material from the system. When placing the system back to automatic mode, the system resumes operation from its prior state in automatic mode. As a result, the person is injured by rotating system components. This is a system accident from the *user's perspective* because the system's actions were unexpected and unplanned. The actions did not fit the user's mental model of operation. The user expected and planned to have the system resume from the last state in manual mode, not the last state in automatic mode. From the designer's perspective, there was no fault of the system because it behaved exactly as it was designed. The *designer's perspective* is that the problem was operator error. Another perspective, possibly of management, is that the problem was human error, and more and better training is needed.

Limited rigorous validation

Perrow validated his theory with a wide variety of illustrative examples from chemical processing, aviation, marine transport, military defense systems, mining, and space missions. Sagan validated the theory using case studies from nuclear weapon systems. Wolf empirically validated the theory using a combination of quantitative and qualitative techniques.

Sagan conducted research to validate NAT by using case studies derived from nuclear weapon safety; the primary test case concerned the Cuban missile crisis of October 1962. Sagan acknowledged that "the study of the commanding control of U.S. nuclear weapons and potential of accidental nuclear war is a tough test for the NAT" (Sagan, 1993 pg 49). "In short the study is a tough test for the Normal Accident Theory. If the NAT does well here, it will be shown to be even stronger than previously estimated" (Sagan, 1993; pg 51). Sagan concluded that there is strong support for NAT, a view counter to his initial beliefs.

Wolf (Wolf, 2000) researched the validity and application of Perrow's theory to petroleum refineries. These are high-risk technical systems having a high degree of process control. Wolf defined a refinery system as a hierarchy of system units, links, and nodes. Refinery complexity depends on the number of unit processes, links, and nodes. Links are the systems pipes that carry raw material, byproducts, final product, and wastes. Nodes are points of connection and interconnection between unit processes and links. They are also the points for control and monitoring of parameters such as flow, pressure, and temperature.

At the system level, refineries employ three types of manufacturing processes: continuous, semi-continuous, and batch. At the unit level, up to 15 distinct processes and a multitude of process technologies can exist.

Wolf's empirical validation utilized a hybrid of quantified and qualified measures for a research sample of 36 petroleum refineries operating from 1992 to 1997. He created a "refinery-specific" index of complexity based on refinery process knowledge. This index served to quantify and estimate the interactive complexity for a refinery. The index of complexity was calculated using the following formula (Wolf, 2000) pg. 65:

$$\mathrm{C}_{iplant} = \prod_{i=1}^{n}\left(\prod_{j=1}^{m}(Q_{ij})\right) = \prod_{i=1}^{n}\ \prod_{j=1}^{m}\ \left(\prod_{k=1}^{r}(Q_{ijk})\right) \qquad \textbf{(3-1)}$$

where

C_{iplant} = Refinery complexity
n = Number of refinery unit processes
m = Number of nodes at process i
r = Number of parameters at node j
Q_{ijk} = Number of possible states of parameter k at node j for process i
Q_{ij} = Number of possible states of all parameters at node j for process i
C_i = Number of possible states of all parameters of all nodes for process i

C_{iplant} is the index of complexity representing the maximum number of states in which the system could exist. Thus C_{iplant} is an index of complexity useful for relative ranking of refineries with respect to complexity.

The second component of Perrow's theory is coupling. Wolf classified coupling based on a classification of the manufacturing process. Continuous processes are more tightly coupled because they are generally invariant, time dependent, highly sequential, and have little slack. Semi-continuous and batch processes are more flexible in terms of timing and sequencing so they are classified as less tightly coupled.

Wolf's conclusions support the validity of Perrow's theory. Refineries characterized by high complexity and tight coupling had more occurrences of accidental releases of hazardous materials and more fires and explosions. However, two limitations are evident in this research.

First, the work is specific to refineries. Thus the quantification measure, index of complexity, is not generalized to other applications, thus limiting its utilization across various application domains. Second, his work is limited to a narrow application domain. Wolf validates Perrow’s theory for a special set of accidents encountered by refineries: untoward releases of hazardous material, fires, and explosions. These are typically encountered in the refinery sector, further illustrating the limitation of his highly specialized research.

Sharit (Sharit, 2000), another researcher utilizing NAT, developed a risk modeling framework incorporating NAT. The model is used to identify system risks, potential human errors, and affords a better understanding of complex systems. Sharit modeled an emergency health care system. We differ with Sharit's view of complexity.

He states "What determines a system's interactive complexity - and establishes whether it is complex or linear - is the presence of a *number* of system features or attributes" (Note: italics added for emphasis.) Sharit is referring to the interactive complexity attributes listed in Table 3-1. His statement infers the *quantity* of system features or attributes alone determines complexity; therefore, quantity determines complexity and all features or attributes have an equal contribution. This view is analogous to counting lines of code to determine complexity. Secondly, it infers that a single number can characterize the multiple dimensions of complexity.

This research does not agree with these inferences and will address the following questions. Do all attributes contribute equally to system complexity, and if not, which attributes contribute the most to complexity? Secondly, this research quantifies complexity in multiple dimensions.

Complexity Metrics

The use of software complexity measures began in the 1970's as a tool to address rising costs of software development. Software maintenance costs were up to 80 percent of software development costs. Complex software was recognized to be harder and costlier to maintain. Today, research in software measurement continues to be quite active. Software complexity measures have broadened their applicability to predict testing costs, development time and effort, numbers of errors, and numerous quality attributes. As the application scope has broadened, the number of complexity measures has mushroomed; Zuse (Zuse, 1991) characterizes 98 complexity measures.

Ince (Ince, 1985) describes three categories of software complexity measures: lexemical counts, graph theoretical, and system design structure. Adding the category of integrated results in the four categories described as follows:

5. Lexemical counts: Count the key language entities such as keywords and operators.
6. Graph theoretical: Graph based control models of the system are created and key graphic characteristics such cyclomatic complexity are calculated.
7. System design structure: The structure is defined in terms of internal and external coupling of subsystems and modules. Internal coupling of modules is named cohesion or strength. Highly cohesive modules are desirable because behavior is localized. The external relationship among modules is called coupling. Loose coupling gives a high degree of isolation which minimizes the interdependency of modules.
8. Integrated: Integrated metrics synthesize existing metrics as a multi-metric composite.

Lexemical counts

The best known lexemical counts are Halstead's metrics, Table 3-3, and lines of code (LOC). Halstead's metrics are based on the measurement of two parameters, operators and operands, where:

n_1 = number of unique or distinct *operators*
N_1 = total usage of all *operators*
n_2 = number of unique or distinct *operands*
N_2 = total usage of all *operands*.

Table 3-3. Halstead metrics.

Metric	Formula
Program length	$N = N_1 + N_2$
Program vocabulary	N = n1 + n2
Volume	$V = N * (LOG_2\ n)$
Difficulty	$D = (n_1/2) * (N_2/n2)$
Effort	E = D * V

Weaknesses in Halstead's metric are listed (Beizer, 1990):

1. Halstead's metric depends on completed code.
2. The metric ignores nested loops.
3. Operators and operands are treated equally.
4. There is no differentiation of operator types (i.e. if-then-else is counted the same as do-while even though, in general, loops are problematic).

LOC, as the name implies, is a count of the lines of code. This metric is fraught with problems such as what constitutes a line for counting (i.e., are comment lines counted?), programming language and style dependencies, and the erroneous notion that size and complexity have a causal relationship.

Graph theoretical

McCabe's cyclomatic complexity metric (McCabe, 1976) is one of the best known graph theoretical metrics. Cyclomatic complexity is a measure of the number of independent control paths for a software program. As a general rule, if the complexity is greater than 10, redesign should be considered. This metric is calculated as:

$$V(g) = e - n + 2 \qquad \textbf{(3-2)}$$

where:

e = number of edges
n = number of nodes

If "n" disconnected graphs exist, the overall complexity is calculated by:

$$V(g)total = \sum_{1}^{n} V\ (g)n \qquad \textbf{(3-3)}$$

Cyclomatic complexity was extended by Vakil to examine and identify system mode transition complexities for a commercial aircraft auto-flight system (Vakil, 2000). He developed a "Hybrid Automation Representation" to model the mode transitions of an auto-flight system. Cyclomatic complexity was used to analyze the mode transitions of this complex system. Vakil found a correlation between mode transitions having high cyclomatic complexity and the apparent complexity, as identified from the perspective of pilots.

McCabe's metric is not devoid of weaknesses (Beizer, 1990) (Fenton & Pfleeger, 1997). First, it assumes a linear relationship of total complexity because the complexity of each part is summed. This effectively underestimates complexity because complexity increases nonlinearly (Beizer, 1990). It also has a weakness concerning compound predicates. Treating a compound predicate as a single construct yields a lower complexity number compared to separating it as series of constructs.

System design structure

Henry and Kafura's fan-in and fan-out metric and various coupling metrics are based on design structure. Henry and Kafura's metric is based on the program dimension of data flow where complexity is a function of fan-in and fan-out. The complexity is calculated as follows:

$$\text{Information flow complexity } M = L\,(\textit{fan-in} \times \textit{fan-out})^2 \qquad \textbf{(3-4)}$$

where:

L = program length (McCabe's metric or LOC can be used)
Fan-in = number of calls into a module plus the number of data structures retrieved by the module
Fan-out = number of calls out of a module plus the number of data structures updated by the module

The results from this metric can be quite misleading. For instance, if either fan-in or fan-out is zero, then the complexity calculation result is zero. Similarly, if a group of simple modules has high reuse, fan-in and fan-out would be quite large; thus, the program complexity calculation becomes quite high even though the overall program is simple.

Other problems with this metric are detailed in a study by Shepard (McDermid, 1990). As a result of this study, a hybrid metric was created to overcome numerous problems with Henry and Kafura's original metric. The hybrid metric, called Shepperd complexity is calculated as Shepperd complexity (M) = (fan-in x fan-out)^2.

However, the results from this metric can also be quite misleading. If either fan-in or fan-out is zero, then the complexity calculation result is zero.

Coupling metrics

Coupling metrics measure the degree of connectivity between the parts of the system. Coupling contributes to complexity thus low coupling is desirable to reduce the likelihood of error propagation, facilitate comprehension, and reduce the likelihood that changes in one part of the system do not affect the other parts of the system.

Myers views coupling as a measure of independence or modularity (Myers, 1974). He defined six types of coupling and ordered them into a coupling scale. The scale, from lowest to highest coupling, is data coupling (best), stamp coupling, control coupling, external coupling, common coupling, and content coupling (worst).

Offutt et al. extended Myers work by quantifying coupling, increasing the scale granularity from six levels to 12, and by measuring coupling in various configurations (Offutt, Harrold, & Kolte, 1993). Coupling could be measured between pairs of modules, from a key module to all other modules, and for the entire system. Secondly, they addressed limitations of other metrics work by considering bi-directional coupling, and by giving prescriptive definitions for each coupling level.

Although Offutt et al. have 12 levels of coupling, none of these the coupling attributes of NAT. Secondly, the metrics work presented is for the subsystem of software; thus, additional research is needed for *system-level metrics* addressing NAT.

Integrated complexity metrics

Integrated complexity metrics synthesize existing metrics into multi-metric composites. Coskun (Coskun & Grabowski, 2001) addressed the challenges of modeling and measuring complexity by using an integrated metrics approach. Coskun's research targets embedded real-time systems for large-scale safety critical host systems. For these systems, safety and reliability are obviously important.

Coskun's approach utilizes an interdisciplinary complexity model encompassing six domains; from this complexity model, four types of complexity are measured. The model utilizes the domains of mathematics, computer science, economics, psychology and cognitive sciences, social science, and system science. For instance, the mathematical domain includes Halstead's metric and McCabe's cyclomatic complexity; the economic approach includes metrics of resource consumption; the social sciences domain includes NAT.

The metrics from these domains have different views, objectives, and measures. The multiple views afforded by the interdisciplinary approach are desirable because a single view can not capture an entire problem space. The multiple objectives, and associated measures to realize these objectives, are somewhat problematic given the application to large-scale safety critical host systems where safety and reliability are very important as stated by the authors. Specifically, some of the metrics don not apply to safety or reliability; these metrics address quality and cost objectives.

Coskun’s research identifies four types of complexity: architectural/ structural complexity, data processing/ reasoning/ functional complexity, user interface complexity, and decision support/ explanation complexity. It is quite desirable to define and measure multiple types of complexity because a single measure can not capture the notion of complexity. The four complexity types are related to various software layers; hence, Coskun's research does not address complexity at the system level. Software metrics alone are not sufficient to address safety or reliability because these are emerging properties of the *system*.

Complexity metric's limited success

Although there is a plethora of complexity measures, there have been limited successes. McDermid (McDermid, 1990) confirms this stating:

> Complexity is both a major problem and an enigma, as there are no easy and effective ways of measuring it. ... There has been a lot of work on software

> complexity measures, but it is widely accepted that these are not adequate and in many cases are misleading...

There are numerous reasons for the limited success of metrics; some reasons concern weaknesses that have been described in the previous sections. Others provide more insight.

Fenton's (Fenton, 1994) analysis of software measurement identifies a fundamental flaw; most measurements lack a basis in measurement theory. T. Capers Jones (Jones & Vouk, 1990) addresses inaccurate metrics. He cites the root cause of inaccurate metrics as "the widespread tendency to use concepts without examining their validity." Existing metrics measure what we understand and what we are able to measure. Also, much metric research has insufficient validation.

While these criticisms of complexity measures may be valid, there is a much broader flaw: many complexity measures exist for the *subsystem of software*, but they do not address the level of the *entire system*. Software does not have physical properties and therefore by itself is not hazardous. Also, each subsystem can be quite simple, but the interconnections among the software, hardware, and environment could result in a very complex system. Hence, complexity must be addressed at the system level.

Summary

This literature review reinforces the validity of NAT but indicates the absence of research for the safety-critical system domain and scientific rigor, and it points out the limitations and inadequacies of metrics research.

A review of work by Perrow, Sagan, and Wolf confirmed the validity of NAT. Perrow originated the theory and validated it with illustrative examples from chemical manufacturing, aviation, marine transport, military defense systems, mining, and space missions. His illustrative validation methodology is a weakness because it lacks the rigor of scientific quantification. Sagan validated the theory using case studies of nuclear weapon systems. Wolf's empirical research has the strongest scientific support; however, this research is limited to the petroleum process industry domain, so the metrics do not adequately transfer to the safety-critical systems domain. A significant weakness of Wolf's metrics concerns the coarse granularity of coupling metrics where the degree of coupling is assigned based upon the total manufacturing process.

Finally, a review of the most common complexity metrics is given for the following categories:

1. *Leximical counts*: Halstead's metrics, LOC
2. *Graph theoretical*: McCabe's cyclomatic complexity
3. *System design structure:* Henry and Kafura's fan-in and fan-out, Shepperd complexity
4. *Integrated metrics:* Coskun's interdisciplinary complexity

This review describes numerous problems with metrics that include measurement ambiguities, potentially misleading results, lack of a measurement theory basis, and the tendency to use concepts without validation. Additionally, these metrics do not directly address interactive complexity and coupling in terms of NAT, and these metrics pertain to the software subsystem; thus, they don't address the complexity of the system.

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CHAPTER 4
SYSTEM FUNCTIONAL REQUIREMENTS MODELING

The objective of this chapter is to select a method to model system functional requirements for safety critical embedded systems such that the model abstraction enables direct or indirect measurement of NAT complexity. A well-defined system model is critical if meaningful metrics are to be developed.

Twelve criteria were established to help guide the selection of a modeling method. The selected modeling method, named Software Cost Reduction (SCR), is described along with its associated tool set.

System Models

A model is useful for abstracting a real-world entity or process so that only the features or characteristics of interest are shown. Models are useful for understanding; they can reduce complexities by removing extraneous aspects and can afford different projections or viewpoints. This becomes especially useful for complex systems because these systems are often multidimensional. A complex system can “look” different depending on the dimension captured by the projection. For instance, viewpoints can capture structural or behavioral aspects, or they can capture a user's perspective by modeling human interactions with the system. There are numerous types of models; some argue that there are too many modeling approaches. One reason for so many models is that each has different strengths, weaknesses, and capabilities; different types of models are needed to investigate different aspects of an entity or process.

In the context of this work, the system model needs to enable direct or indirect measurement of the NAT attributes captured by the system requirements. Generally, system requirements define "what" the system does − the system's behavior. Design requirements and specifications define the "how" − the system's structure.

System behavioral requirements, also called functional or operational requirements, specify the system inputs (stimuli), the system outputs (responses), and the behavioral relationships between the inputs and outputs. Nonfunctional requirements impose various resource, timing, and performance constraints.

Thus, a model must be constructed with a specific purpose or objective in mind. Selecting a model suitable for one's objectives can be a time-consuming task given the plethora of modeling types, methods, and tools. To simplify the selection of a model for our research, we limit the modeling to the system requirements phase and establish criteria for modeling safety critical embedded systems.

Overview of Model Types, Methods, and Tools

Requirements models can be categorized by three types: natural language, semi-formal, and formal (Loucopoulos & Karakostas, 1995). Natural language is very flexible but it is very difficult to precisely define the system because of language ambiguities. Semiformal models include diagrams and tables. These have fewer ambiguities and interpretations. Formal methods are very exacting and have a rigorous mathematical foundation.

A categorization of functional requirements modeling and analysis is depicted in Figure 4-1 (Easterbrook, 2001) where the most well-known semiformal and formal methods for functional requirements modeling.

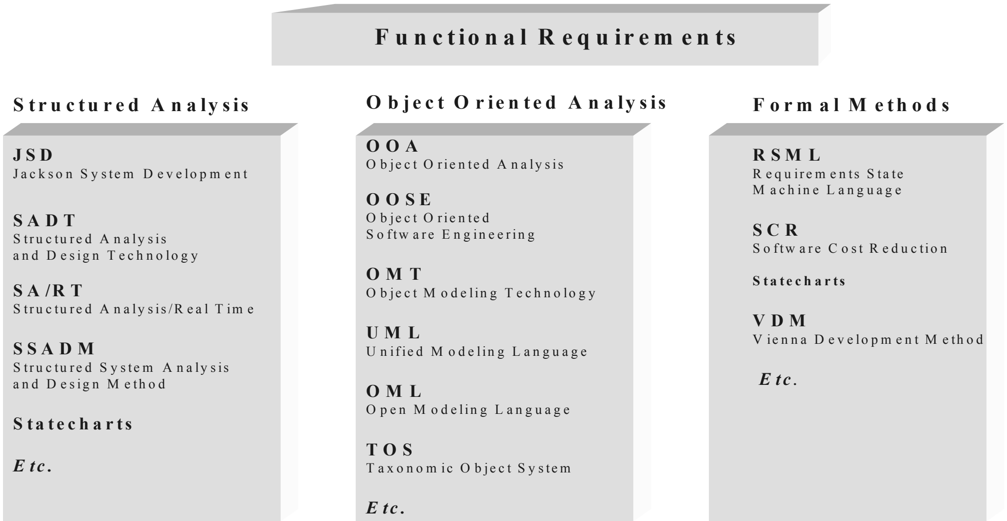
Functional Requirements
Structured Analysis
JSD
Jackson System Development
SADT
Structured Analysis and Design Technology
SA/RT
Structured Analysis/Real Time
SSADM
Structured System Analysis and Design Method
Statecharts
Etc.
Object Oriented Analysis
OOA
Object Oriented Analysis
OOSE
Object Oriented Software Engineering
OMT
Object Modeling Technology
UML
Unified Modeling Language
OML
Open Modeling Language
TOS
Taxonomic Object System
Etc.
Formal Methods
RSML
Requirements State Machine Language
SCR
Software Cost Reduction
Statecharts
VDM
Vienna Development Method
Etc.

Figure 4-1. An overview of requirements modeling methods. Source: Adapted and extended from Easterbrook, 2001.

Requirements Modeling Criteria

Models have different strengths, weaknesses, and purposes; different types of models are needed to investigate different aspects of an entity or process (Easterbrook, 2001). Therefore, criteria are established for selecting a modeling method that is consistent with the objectives and delimitations of this dissertation. The criteria guide the selection of an *appropriate* modeling method and are not utilized as a means to determine the *optimal* modeling method for the research.

Specific Criteria

- *Abstraction Level:* The model must be applicable to the level of the *system* not just the subsystem of software, because safety and complexity are emergent properties of the entire system.
- *Availability:* The modeling technique and associated tools should be widely available to researchers and practitioners.
- *Learning Curve:* It should be relatively easy to learn so that resources can focus on the research and not learning the method and tools.
- *Life cycle phase:* The modeling technique and associated tools must be applicable to the requirements phase.

- *Projection:* The projection needs to capture the end-user's viewpoint in order to investigate the externally visible behavior of the system.

- *Time:* Often, safety-critical embedded systems are real-time, so the model should be able to incorporate timing constraints.

- *Real-world applicability:* The model should be of "industrial" strength so that it can handle the complexity and size of real-world problems as evidenced by a history of real-world utilization.

- *Safety:* Undesirable or unexpected system behavior can create a hazard. This type of behavior can occur during normal system operation or abnormal conditions. System accidents can occur when the end-user improperly responds to or fails to respond to normal or abnormal conditions. Therefore, the model must be able to model behavior for normal and abnormal conditions.

- *Simulation:* Capabilities should exist to interactively execute the specification. This interaction should be available to the model developer for analysis purposes, and to enable human interaction with the system.

- *System Type:* The model must be applicable to safety-critical embedded systems. Often, these systems are reactive, so the model must capture the system's behavior to external stimuli from the environment and liveware.

- *Tools:* The model should have tools, preferably computer-based, to support the creation, modification and analysis of the model.

- *User-interface support:* The model's tools should support extensions for a graphical user-interface to enable end-user interaction with the system.

Of the methods depicted by Figure 4-1, only unified modeling language (UML) and SCR were able to meet most of these criteria. UML is a well-known language for object-oriented analysis and design. UML was not selected because it did not meet the "learning curve" criterion concerning the ease of learning. As whole, UML is complex. The UML 1.3 specification has over 800 pages and UML has numerous modeling diagrams:

- Use case diagrams
- Class diagrams
- Sequence diagrams
- Component diagrams
- Statechart diagrams
- Collaboration diagrams

UML also has several limitations (Glinz, 2000) concerning use case diagrams. These diagrams are used in the early requirements stages to describe how the system interacts with the external actors. Lastly, UML does have commercially available tools; however, these tools are not free as is the SCR set of tools. Although UML has several limitations, this does not infer that UML is unsuitable to model system requirements; all modeling languages have some limitations. UML models have been successfully used to analyze software quality and architectural risks (Yacoub, Ammar, & Mili, 2000).

The SCR method was chosen because of the Navel Research Laboratory's (NRL) interest in this research and their willingness to give access to SCR knowledge, experience, and SCR tools at no cost.

Software Cost Reduction (SCR) for Requirements

SCR was originally used for documenting and specifying the functional requirements of the A-7-E aircraft's Operational Flight Program (Queins et al., 2000). SCR is a powerful method for the formal specification, analysis, and validation of complex, embedded systems for a variety of systems including telephone networks, avionics, safety-critical control systems for nuclear power plants, and the International Space Station. During the mid 1990's, SCR was extended from software requirements to system requirements; these extensions included the incorporation of *nonfunctional requirements* such as timing and accuracy constraints. Additionally, NRL developed support for integrated tools called the SCR* tool set.

The SCR method formalizes functional behavior as mathematical relations. These relations are part of the Parnas Four-Variable Model. This is a model of requirements that is essentially a black box view of system inputs, outputs, and external behavior; thus, the model captures the required external behavior, devoid of implementation or structural aspects of the design. SCR also employs tables with a relatively simple formal notation to define mathematical functions; hence, SCR tables facilitate industry utilization because the tables and the notation are easily created and understood (Heninger, Parnas, Shore, & Kallander, 1978).

SCR Four-Variable Model

The Four-Variable Model partitions a system into four elements: the environment, input devices, software, and output devices. The model's projection captures synchronous behavior, as viewed externally, and hardware/software interfaces to the environment. The external behavior is from the perspective of the user, although the model does not explicitly depict the user as part of the system as in the SHEL model. Because, in the context of this work, complexities are from the user's perspective, we extend the Parnas Four-Variable Model to include the liveware element of the SHEL model. This model extension is depicted by Figure 4-2.

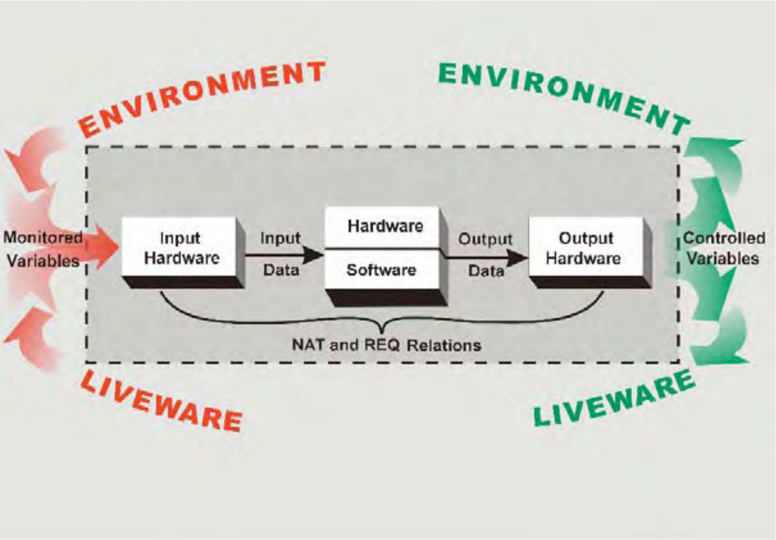

Figure 4-2. The SCR Four-Variable Model extended to incorporate the SHEL model

The required behavior is formalized by the Four-Variable Model as follows (Heninger et al., 1978):

> The Four-Variable Model . . . describes the required system behavior, including the required timing and accuracy, as a set of mathematical relations on four sets of variables—monitored and controlled variables and input and output data items. A *monitored variable* represents an environmental quantity that influences system behavior, a *controlled variable* [is] an environmental quantity that the system controls. A black-box specification of required behavior is given as two relations, **REQ** and **NAT**, from the monitored to the controlled quantities. NAT, which defines the set of possible values, describes the natural constraints on the system behavior, such as constraints imposed by physical laws and the system environment. **REQ** defines additional constraints on the system to be built as relations the system must maintain between the monitored and the controlled quantities.
>
> In the Four-Variable Model, input devices (e.g., sensors) measure the monitored quantities and output devices set the controlled quantities; input and output data items represent the values that the devices read and write.

SCR represents monitored and controlled quantities as variables. The dependent variables are the controlled variables, mode classes, and terms; the independent variable is the monitored variable.

To summarize the flow through the Four-Variable Model, monitored and controlled quantities are within the environment's domain; input devices transform monitored quantities to input data that are represented by SCR models as monitored variables; output devices transform output data, represented by SCR models as controlled variables, such that the controlled quantities are manipulated.

The system's behavioral requirements are defined by the **NAT** and **REQ** relations for *ideal behavior*. These relations can be extended to *non-ideal* behavior encountered in the real world. Non-ideal behavior specifies the response to undesired events. Sources for non-ideal behavior include hardware malfunctions or incorrect human interactions with the system. The non-ideal behavior combined with the ideal behavior is defined by the $\overline{\boldsymbol{NAT}}$ relation.

SCR Terminology and Notation

The basic concepts of SCR have been presented. SCR terminology and notation (Heitmeyer, 1996) is presented in order to establish a common understanding of SCR specifications.

Condition: A condition *c* is a logical expression for an input or output variable, mode, or term. Conditions may be simple or compound.

Condition Table: This table defines a given controlled variable or term as a function of the possible modes and associated conditions for each mode. Thus, it defines the value of controlled variables or terms for all conditions.

Event: An event *e* is an instance in time when a mode, term, or variable changes value. For instance, an input event occurs when a monitored quantity changes; an output event occurs when a controlled quantity changes.

$e = @T(c)$; a basic event where condition *c* changes to true
$e = @F(c) = @T(\neg c)$; a basic event where condition *c* changes to false
$e = @T(c)$ WHEN $d = a \wedge a'$; an event where a = next state, a' = old state

Event Table: This table defines a given controlled variable or term as a function of the possible modes and associated events for each mode. Thus, it defines the response of controlled variables or terms to input events.

Mode: A state of the environment as represented by monitored variables.

Mode Class: A type of deterministic synchronous finite state machine comprised of modes that partition the state of the environment. Complex systems have multiple mode classes operating in parallel.

Mode Transition Table: A "state table" consisting of “source modes" (present state), "destination modes" (next state), and events that cause a transition. Each row of this table is disjoint.

System: A system $\sum$ is a 4-tuple

$$\sum = (E^m, S, s^0, T) \qquad \textbf{(4-1)}$$

where:

$E^m =$ set of input events,
$S =$ set of system states,
$s^0 =$ set of initial states where $s^0 \subseteq S$
$T =$ the system transform

Term: An internal variable defined by the SCR user. A term's value is defined by condition and event tables. A frequently used expression can be assigned to a term to simplify an SCR specification.

SCR Requirements Specification

Requirements are commonly conveyed and documented by a requirements definition document written in prose. The SCR methodology translates this prose into a formal SCR specification. The major components of an SCR specification are depicted by Figure 4-3. The SCR specification consists of three tables, five dictionaries, and miscellaneous information.

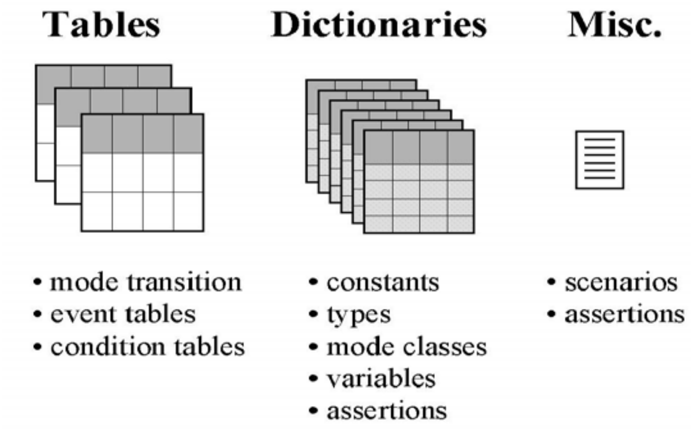

Figure 4-3. The elements of an SCR specification.

SCR specifications use condition, event, and mode transition tables to define functions. The dictionaries define variables, types, constants, mode classes, and assertions. Scenarios are composed of input event sequences and are used for simulation purposes. Assertions define properties that must hold for the system. Typically, these are safety and security properties.

Time and performance constraints can be incorporated into the SCR specification (Heitmeyer, 1996). Time is represented by a monitored variable and is a non-negative integer initialized to zero.

SCR*toolset

The NRL created the SCR*toolset (Maurer, 2000) to support the SCR methodology. The tool set is an integrated suite of CASE tools publicly available from NRL. The tool set has found relatively widespread use; it has been installed at over 100 organizations in industry, government, and academia, according to Heitmeyer (personal communication, 2000).

The components of the SCR*toolset are shown in figure 4-4. This figure also depicts the basic process of using the tool set to translate a requirements specification to an SCR specification, analyze the specification, and validate the external behavior by simulation.

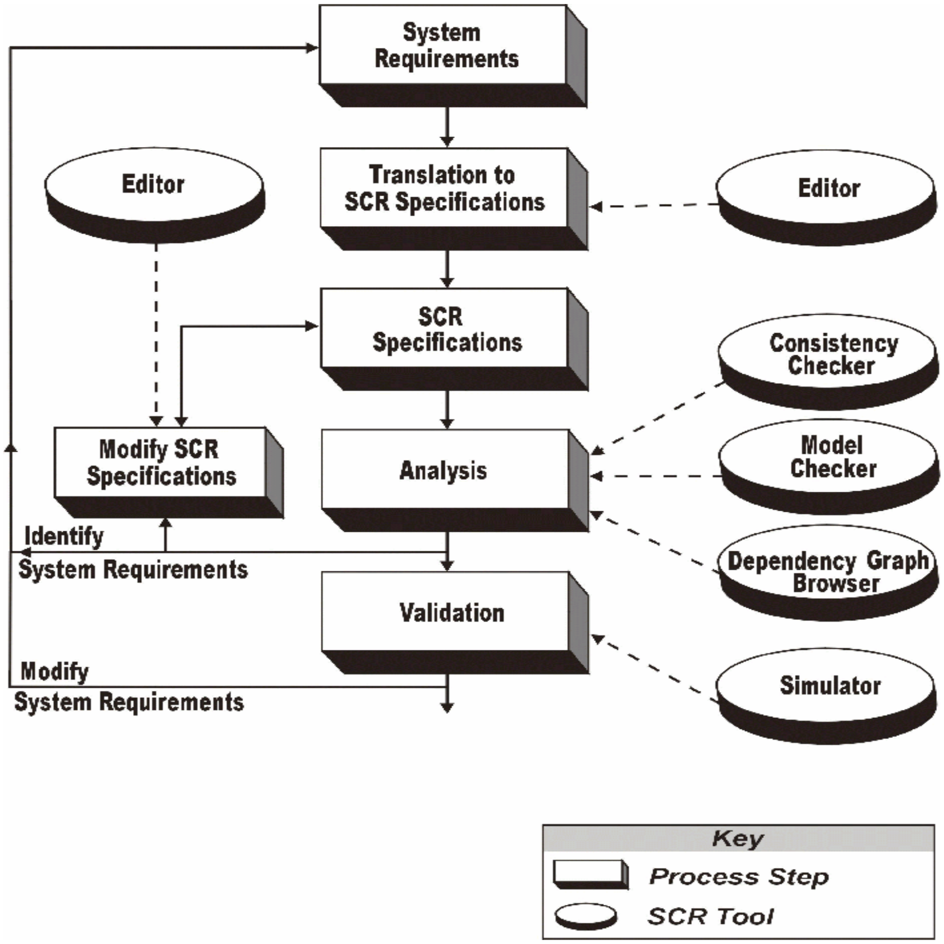

Figure 4-4. The SCR tools integrated with the various steps to analyze and validate system requirements.

The editor tool is used to create, view, and modify an SCR specification. Analysis of the specification is done with consistency checking and model checking tools. The consistency checking tool is used to identify specification ambiguities, including incompleteness or inconsistencies, and also problems with syntax, types, and circular dependencies. Model checking is used for verification of the specification and properties. The simulator tool is used to create a graphical user interface (GUI) and to run a simulation. The simulator is also used to validate the requirements and system properties.

A second type of analysis is possible by utilizing SCR visualization tools. The dependency graph browser, Figure 4-5, displays the dependencies between SCR model variables (the controlled and monitored variables, modes, and terms) and gives a graphical overview of the specification. It also provides a mapping of controlled variables to monitored variables. The graph depicts each SCR variable as a node; a dependency between nodes is represented by an arrow where the variable's value at the tail depends on its value at the head of the arrow.

A second graph is called the mode transition graph which is much like a state transition diagram. A mode transition graph exists for each mode class.

The vertices or nodes represent modes and the directed arcs represent transitions. Figure 4-6 shows an example mode transition graph, comprised of the modes (states) Low, Normal, Voter Failure, for a mode class named M_Pressure.

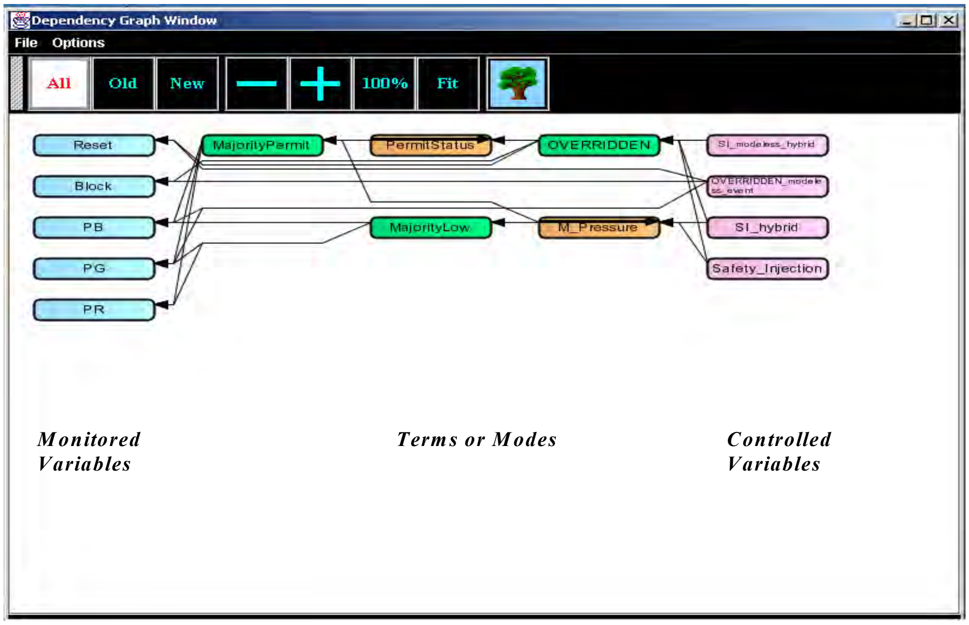

Figure 4-5. An SCR dependency graph. Source: Navel Research Laboratories

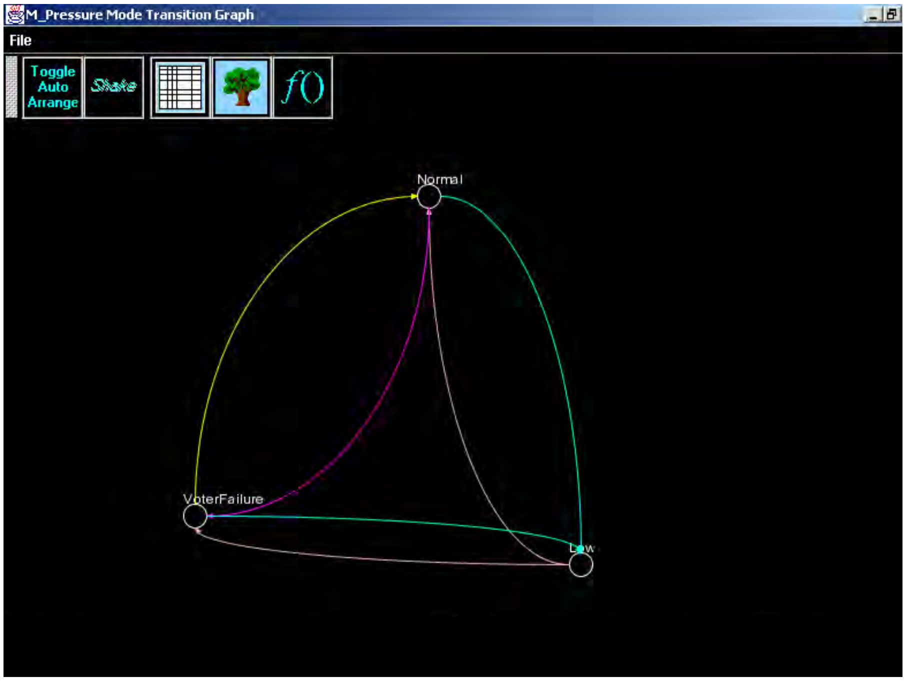

Figure 4-6. A mode transition graph for the mode class "M_Pressure" Source: Navel Research Laboratories

Summary

One of the first steps in the measurement process is to define the object or process to be measured. Next, a systematic method is needed to determine what needs to be measured and what abstraction or model can enable measurements. This chapter established 12 criteria to help guide the selection of a modeling method. Based on these criteria, the SCR method was selected. SCR and the supporting set of tools were described in detail.

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CHAPTER 5
COMPLEXITY METRICS

A graph-theoretical approach was used to operationalize NAT. Our objective was to define multiple, graph-theoretical metrics to measure or indicate specific NAT attributes of a system. The specific NAT attributes to operationalize are identified by a three-step, systematic process.

Our approach also addresses the limitations of NAT and of other metric research, described in the literature review of Chapter 3, by using multiple system abstractions and perspectives to obtain metrics that can be precisely defined and quantified. Three levels of system abstraction and three projections are used capture the multidimensional aspects of complexity.

As a result, fifteen graph-theoretical metrics are proposed as measures or indicators of specific NAT attributes of complex systems.

Graph Theory

Background information on graph theory is presented to establish terms and definitions. Graph theory is useful for modeling and analyzing a variety of empirical systems such as electrical circuits, communication networks, and transportation scheduling networks. Graphs depict connections and relationships between a system's elements and subsystems thus enabling quantification of a system's logic structure.

A large body of knowledge exists for graph theory. It has been studied since the 18th century; thus, the precise definitions, theorems, and axioms of graph theory are very useful for this research.

Background information on graph theory is presented just to establish a common understanding of terms and definitions. Next, examples are given showing how each metric was calculated from SCR dependency graphs and SCR state information.

The SCR Dependency Graph

The SCR dependency graph represents mathematical relations as defined by the SCR specification. The dependency graph, represented as *G = (V, E),* satisfies the following:

- *V(G):* a finite, non-empty set of *vertices*.
- *E(G):* a finite set of ordered pairs (*u,v*)of vertices called *edges* or *directed edges.*
- For *E(G),* no two directed edges are parallel.
- For *E(G),* a self loop is an edge $e = (u,u)$ starting and ending at vertex *u*.

Definitions:

Ancestors: The set of all ancestors anc(u) = $\{u \in U$: there exists $(u, v) \in E\}$.

Cyclomatic complexity: also known as the nullity of a graph. The number of linearly independent paths;

$$\text{V (g)} = \text{e} - \text{n} + 2 \qquad \textbf{(5-1)}$$

where:

e = number of edges
n = number of nodes

If "n" disconnected graphs exist, the overall complexity is calculated by:

$$\text{V (g) total} = \sum_{1}^{n} V \text{ (g) n} \qquad \textbf{(5-2)}$$

Descendent: The set of all descendents dep(u) = $\{v \in V$: there exists $(u, v) \in E\}$.

Direct ancestor: For (u,v), *u* is a direct ancestor of *v*.

Direct descendent: For (u,v), *v* is a successor or direct descendent of *u*.

Direct edge: An edge is represented by an arrow with a starting and ending point. A directed edge $e = (u,v)$ starts at vertex u and ends at vertex v.

Graph degree: The sum of the in-degree and out-degree for a graph.

In-degree: The number of edges ending at a vertex. The in-degree id(u) of a vertex u is the number of edges (v, u) for all $v \in V(G)$. In-degree is also known as fan-in.

Independent path: A linearly independent path contains at least one new vertex or edge.

Input vertex: If id(v) = 0, then v is an source or input

Local degree: The local degree of a vertex is the sum of the in-degree and the out-degree.

Out-degree: The number of edges starting at a vertex. The out-degree od(v) of a vertex v is the number of edges (u, v) for all $v \in V(G)$. Out-degree is also known as fan-out.

Output vertex: If od(v) = 0, then v is an destination or output.

Scenario subgraph: A subgraph S induced by the set of vertices involved by a scenario as simulated by the SCR simulator.

Self loop: An edge $e = (u,u)$ starting and ending at vertex u.

Shepard complexity (M) = (id(v) x od(v))^2.

Strict semipath: A joining of vertex *v1*, to vertex *vn* such that they are not mutually reachable. For example, in Figure 5-1, a strict semipath joins *v1* and *v3*.

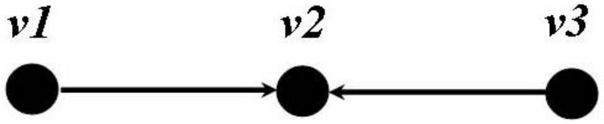

Figure 5-1. The vertices *v1* and *v3* are not mutually reachable because a strict semipath joins them.

Subgraph: A graph S whose vertices and edges are vertexes and edges of a graph G. The subgraph S is induced by a set of vertices of graph G.

Vertex: A vertex v is represented as a rectangle in a SCR dependency diagram.

Specific Attributes of Normal Accident Theory (NAT)

We revisited NAT with the objective of defining multiple, graph-theoretical metrics to measure or indicate specific NAT attributes of a complex system. Specific NAT the attributes to operationalize are identified by a process of deduction: 1) abstracting Perrow's thirteen attributes of complexity to a generalized view of simple (linear) and complex (nonlinear) systems; 2) selecting a subset of NAT attributes pertaining to linear and nonlinear systems; 3) identifying a general set of metrics to measure or indicate the subset of NAT attributes.

First, the definition of complexity is established. Webster's dictionary defines complexity as follows:

> Complexity: (a) having many varied interrelated parts, patterns, or elements and consequently hard to understand fully; (b) marked by and involvement of many parts, aspects, details, notions, and necessitating earnest study or examination to understand or cope with (Gove, 1996).

This definition supports the structural and psychological aspects of NAT complexity. Part (a) addresses the structural components of interconnections and coupling; part (b) concerns the psychological component of comprehension and confusion. Our primary interest is in the structural aspects of complexity evident in SCR dependency graphs. Next, we review NAT attributes.

Perrow lists these thirteen attributes of complex systems (Perrow, 1999):

- close proximity
- common-mode connections
- many interconnections
- limited substitutions
- many feedback loops
- poor information quality
- limited or incorrect comprehension
- strict time-dependencies
- invariant sequences
- inflexible
- limited slack
- limited substitutions
- interacting control parameters

Perrow also draws a major distinction between simple and complex systems: simple systems are linear; nonlinear systems are complex.

Linear and Nonlinear Systems

Simple systems are linear; they do not have multiple branching paths interconnecting system components and subsystems. A linear path is physically and logically separated from other system parts; so, the path follows a predictable, sequential order. A linear system is given involving a single line of dominos. A single disturbance of a domino starts a linear chain of events where one domino pushes over the next. This chain of events follows a highly observable, predictable, and linear sequence.

Nonlinear systems are complex because they are highly interconnected and interactive. A single input or failure can generate many nonlinear branching paths between system components and subsystems. These interactions can be unexpected, unplanned, and incomprehensible to system users. A nonlinear system example is given involving a car windshield. A single disturbance, such as a stone hitting the windshield, causes a multitude of nonlinear, interconnected cracks. The chain of events from a single stone, with respect to the cracks, is highly unpredictable and nonlinear because the stone does not create a single, isolated crack.

A subset of NAT attributes

We used the high-level NAT abstraction of linear and nonlinear systems to focus the scope of the problem of operationalizing NAT. As stated earlier, we are interested in the structural aspects of complexity. Linearity is a structural aspect of system; therefore, we determine a subset of Perrow's thirteen NAT attributes pertaining to linearity. More specifically, we select the NAT attributes present in SCR dependency graphs.

The resulting NAT attributes for linearity are as follows:

- Interconnectivity
- Common-mode connections
- Multiple, interacting control parameters

NAT attribute metrics

The third step of our process was to identify multiple metrics to measure or indicate the specific NAT attributes of interconnectivity, common-mode connections, and multiple, interactive control parameters.

We used graph theory to formally define metrics for interconnectivity. Figure 5-2 depicts a simple linear system. The linearity of this system can be quantified by measuring the interconnectivity between vertices. In this example, the interconnectivity is established by the path *v1, v2, v3*, and *v4*. More formally, the cyclomatic complexity metric V (g) is indicative of the system's interconnectivity. V (g) quantifies the number of linearly independent paths where, for Figure 5-2, V (g) = 1.

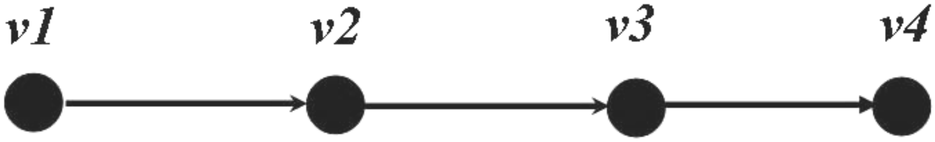

Figure 5-2. A simple linear system with one linear path *v1, v2, v3*, and *v4.*

Figure 5-3 depicts a nonlinear system with the same set of vertices {*v1, v2, v3, v4*}; however, this system is highly interconnected. The cyclomatic complexity of Figure 5-3 is V (g) = 5.

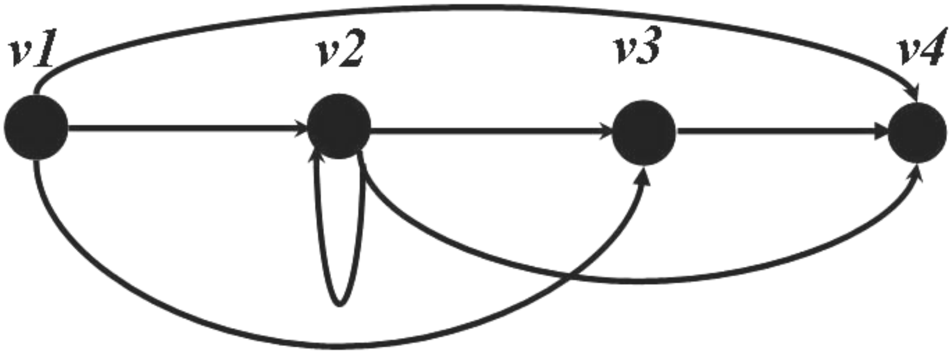

Figure 5-3. A nonlinear system. This system has the same vertices {*v1, v2, v3, v4*} as the linear system of Figure 5-2; however, it has five linearly independent paths.

The process of operalization necessitates identification of multiple metrics for each variable to be operationalized. We identified three metrics in addition to cyclomatic complexity: the graph degree, number of paths, and Shepard complexity. Next, we addressed the attribute of common-mode connections.

Vertices *v2*, *v3*, and *v4* of Figure 5-3 have a common-mode connection established by vertex *v1*. Vertex *v2* is another common-mode connecting *v2* to *v3*, *v4*, and to itself via a self loop. The out-degree metric quantifies a common-mode connection. The out-degrees of vertices *v1*and *v3* are od(*v1*) = 3 and od(*v2*) = 3. We quantify the common-mode connections for a graph by summing the out-degree of each vertex. Next, we addressed the third NAT attribute: multiple, interacting control parameters.

Control parameters are used to determine the paths of control in a graph. For instance, vertex *v2* of Figure 5-3 has two output paths and two inputs. The output path is determined by the parameters associated with inputs from *v1* and *v2*. The number of vertex inputs is indicative of the quantity of control parameters for that vertex; thus, the in-degree was used as an indicator of the number of control parameters. We quantify the number of control parameters for a graph by summing the in-degree of each vertex. The graph of Figure 5-3 depicts the edges connecting vertices, but not the actual values associated with each edge. This graphical abstraction does not contain enough detail, so we look at other aspects of an SCR model to identify two more metrics: the number of unique control conditions and the number of critical state changes. These metrics required a more fined-grained abstraction so they are explained in a subsequent section.

In summary, we identified three NAT attributes and proposed seven general metrics as depicted by Figure 5-4.

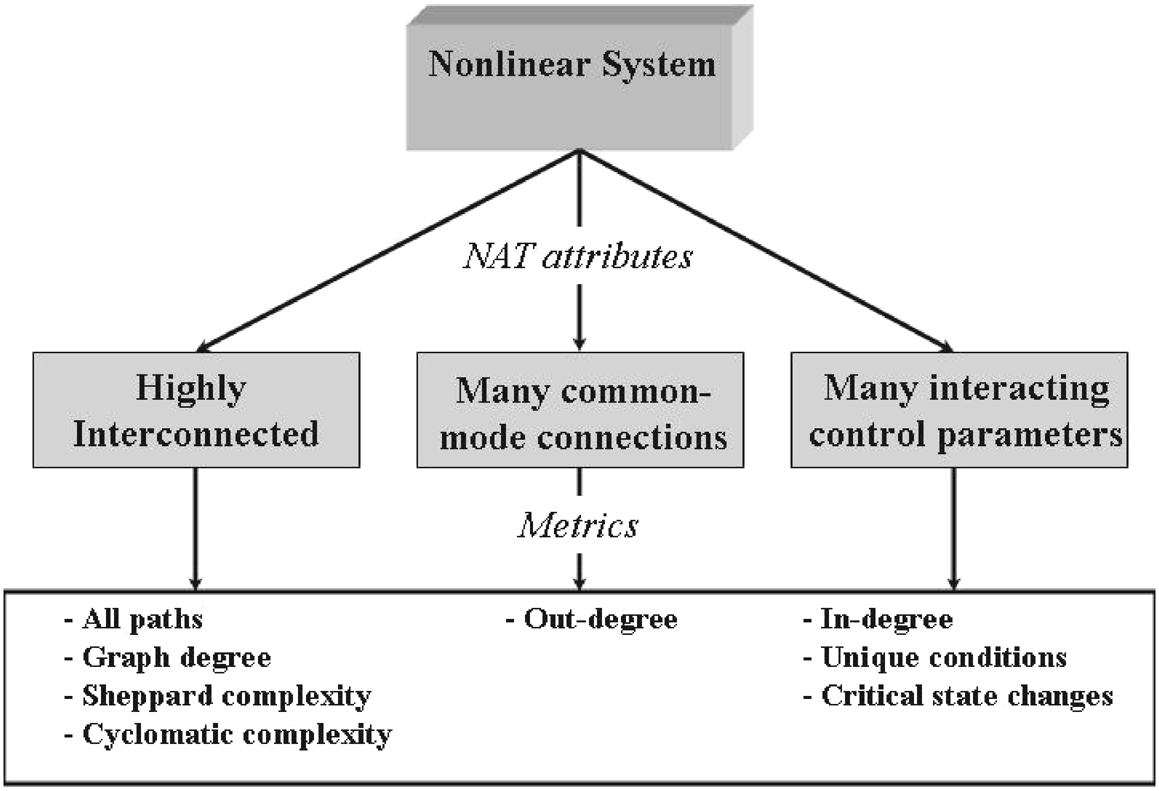

Figure 5-4. The NAT attributes and the proposed metrics of system linearity.

Metric Descriptions

Our approach to operationalize NAT addressed limitations of NAT and other metric research as described in the literature review of chapter 3 by using:

- multiple metrics to quantify each NAT attribute
- three system abstractions for the metrics.
- three projections for each system abstraction

Three system abstractions

Three system abstractions were used in the process of determining metrics for NAT attributes. The rational was that it was unlikely a single abstraction would contain all the metrics because complexity is a multi-dimensional. Therefore, multiple abstractions were needed. The following abstractions were created:

- the scenario subgraph, a course-grained abstraction;
- the critical-state subgraph, a medium-grained abstraction;
- the critical-vertex subgraph; a fine-grained abstraction.

Scenario subgraph abstraction

The first level of abstraction is named the scenario subgraph. This course-grained abstraction of an SCR dependency graph was defined by the subgraph induced by the edges and vertices used during a scenario; therefore, unused edges and vertices are eliminated. For example, Figure 5-5 depicts an SCR dependency graph of a system. The highlighted (darkened) vertices are those used during a given scenario. Figure 5-6 depicts the resulting scenario subgraph of only the vertices and edges used for a given scenario.

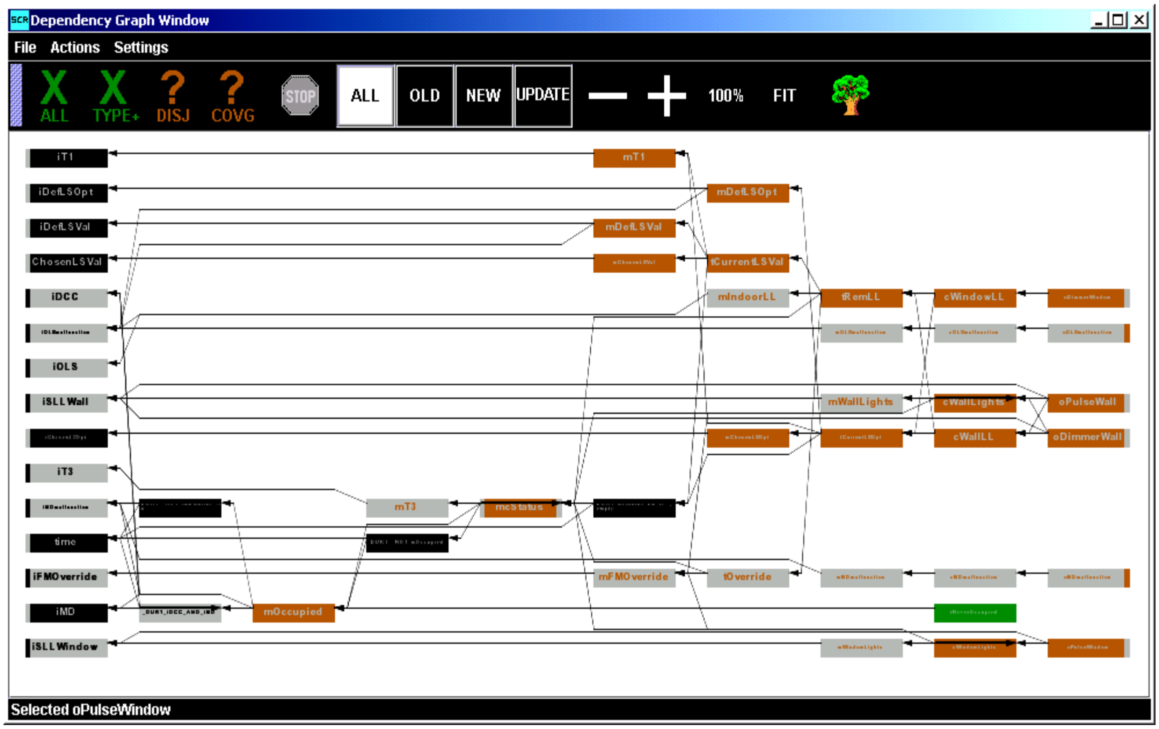

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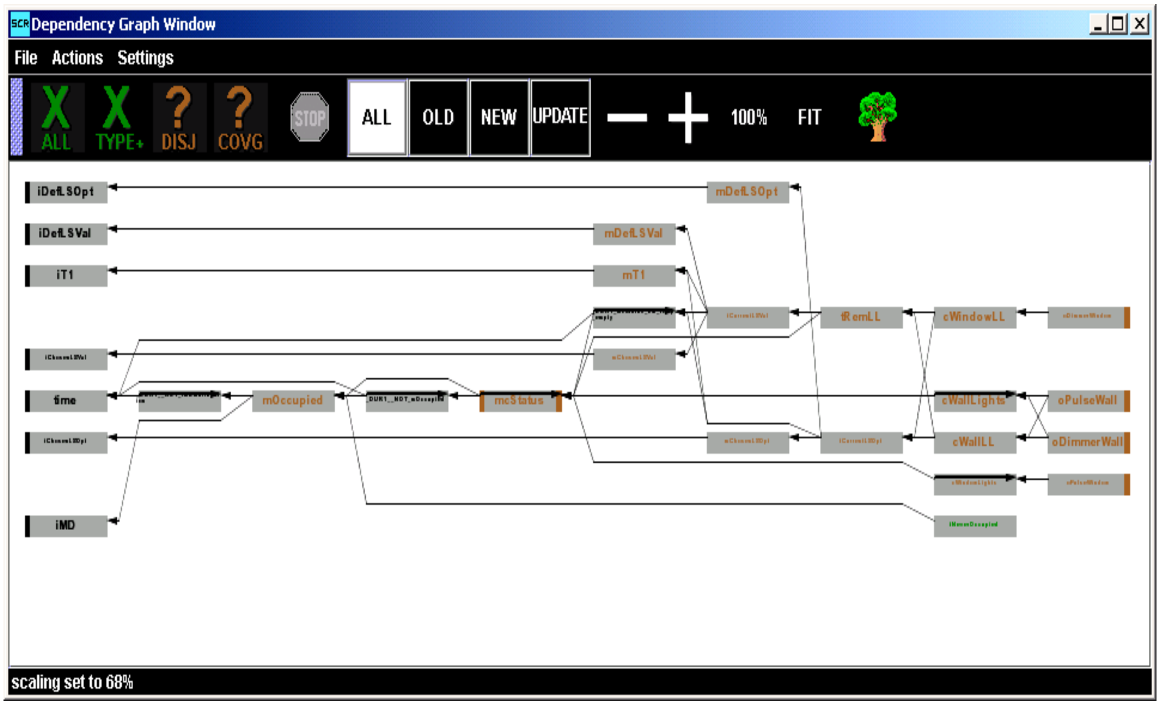
Figure 5-5. An SCR dependency graph of all dependencies for a given system. The highlighted vertices are those used for a given scenario.



scaling set to 68%

Figure 5-6. The scenario subgraph induced from the graph of Figure 5-5.

Critical-state subgraph abstraction

A critical-state subgraph is induced from the vertices of a critical state. These vertices are determined from inspection of an SCR log file; an ASCII file generated by the SCR Simulator. We explain the SCR log file before describing a critical state.

The SCR log file contains a listing of initial state conditions and a sequential list of all state changes during an SCR simulation. Table 5-1 lists an excerpt of the fourth and fifth state from an SCR log file and serves to explain the log file contents. Note that all input variables are listed on the left and all other variables are listed on the right side of the log excerpt. Also note that each variable of the log file is a dependency graph vertex.

Table 5-1. An SCR log file listing the variables that changed at state four and five. The input variables, listed on the left, caused the sate changes.

Input variables	All other variables
--- State 4 ---	
iChosenLSVal = 4307	mChosenLSVal = 4307
	tCurrentLSVal = 4307
	tRemLL = 4307
	cWindowLL = 4307
	oDimmerWindow = 86
	oWindowOutput = 86
--- State 5 ---	
iChosenLSVal = 7591	mChosenLSVal = 7591
	tCurrentLSVal = 7591
	tRemLL = 7591
	cWallLL = 2591
	oDimmerWall = 51
	oWallOutput = 51
	cWindowLL = 5000
	oDimmerWindow = 100
	oWindowOutput = 100

State changes occur when the value of an SCR input variable changes. Table 5-1 lists the fourth and fifth state change; state four occurred when the input variable *i*ChosenLSVal changed to a 4307; state five occurred when the input variable *i*ChosenLSVal changed to 7591. Nine other SCR variables, listed on the right side of Table 5-1, changed values when *i*ChosenLSVal changed at state five.

We now explain the concept of a critical state. Table 5-2 contains a partial listing of two log files. The log file listing in the left column was generated by an SCR simulation of an SCR specification named treatment A; the other log file listing in the right column is from an SCR simulation of an SCR specification named Treatment B.

Table 5-2. A comparative listing of state 5 from two SCR log files.

Log file from treatment A		Log file from treatment B.	
Input variables	All other variables	Input variables	All other variables
--- State 5 --		--- State 5 ----------------------	
iChosenLSVal = 7591		iChosenLSVal = 7591	
	mChosenLSVal=7591		mChosenLSVal= 7591
	tCurrentLSVal=7591		tCurrentLSVal = 7591
	tRemLL =7591		tRemLL = 7591
	cWallLL = 2591		cWindowLL = 5000
	oDimmerWall = 51		oDimWindow = 100
	oWallOutput = 51		oWindowOut = 100
	cWindowLL = 5000		
	oDimWindow =100		
	oWindowOut=100		

Note that all other state information up to state five was identical for both log files. This state information was redundant so, it is of little use. State 5 is named the critical state because as we investigated which is more complex, treatment A or B, it was critical to focus on the information for states that differed. Hence, state 5 was a critical state.

The SCR variables for the critical state comprise the vertices of the critical-state subgraph. For example, state 5 is a critical state for two SCR specifications and is depicted by Table 5-2. Each variable of Table 5-2 defines a vertex of the critical-state subgraph. For instance, Figure 5-7 depicts the critical-state subgraph for state 5 of SCR specification treatment A. Observe that a single input variable change of *i*ChosenLSVal = 7591 caused nine other SCR variables to change as shown by Figure 5-7.

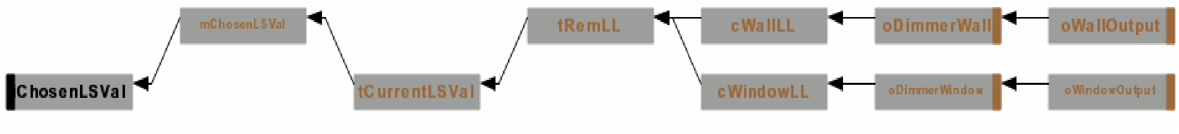
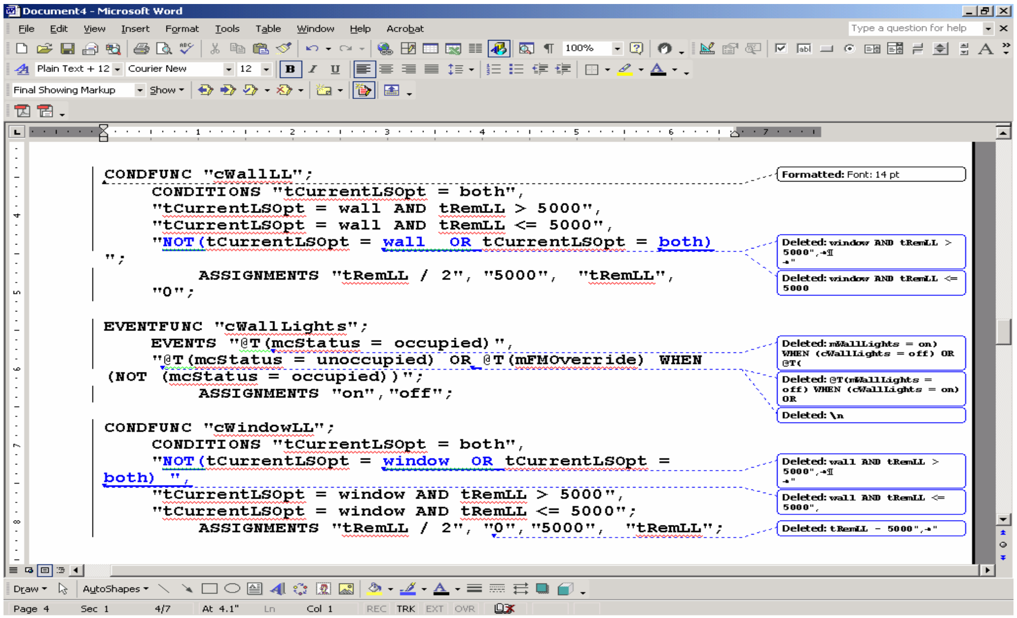


Figure 5-7. The critical-state subgraph for state 5 of SCR specification treatment A. The subgraph is defined by the variable changes listed by the log file of Table 5-2.

Critical-vertex subgraph abstraction

The third abstraction is named the critical-vertex subgraph. This fine-grained abstraction is defined by critical vertices of the scenario subgraph. The critical vertex uses the same concept as the critical state; eliminate redundant information to reveal the critical information. Hence, critical vertices are those that differ between two scenarios.

Comparing the SCR specification files of two systems enabled identification of critical vertices. The SCR specification file can be opened as ASCII text by using a word processor. Next, using the word processor's document compare function, we identified the differences between two SCR specifications as shown by Figure 5-8.


Document4 - Microsoft Word
File Edit View Insert Format Tools Table Window Help Acrobat
Type a question for help
Plain Text + 12
Courier New
12
Final Showing Markup
Show
Draw
AutoShapes
Page 4 Sec 1 4/7 At 4.1" Ln Col 1 REC TRK EXT OVR

```
CONDFUNC "cWallLL";
     CONDITIONS "tCurrentLSOpt = both",
     "tCurrentLSOpt = wall AND tRemLL > 5000",
     "tCurrentLSOpt = wall AND tRemLL <= 5000",
     "NOT(tCurrentLSOpt = wall  OR tCurrentLSOpt = both)
";
          ASSIGNMENTS "tRemLL / 2", "5000",  "tRemLL",
     "0";

EVENTFUNC "cWallLights";
     EVENTS "@T(mcStatus = occupied)",
     "@T(mcStatus = unoccupied) OR @T(mFMOverride) WHEN
(NOT (mcStatus = occupied))";
          ASSIGNMENTS "on","off";

CONDFUNC "cWindowLL";
     CONDITIONS "tCurrentLSOpt = both",
     "NOT(tCurrentLSOpt = window  OR tCurrentLSOpt =
both) ",
     "tCurrentLSOpt = window AND tRemLL > 5000",
     "tCurrentLSOpt = window AND tRemLL <= 5000";
          ASSIGNMENTS "tRemLL / 2", "0","5000",  "tRemLL";
```

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Deleted: window AND tRemLL > 5000",¶ "

Deleted: window AND tRemLL <= 5000

Deleted: mWallLights = on) WHEN (cWallLights = off) OR @T(

Deleted: @T(mWallLights = off) WHEN (cWallLights = on) OR

Deleted: \n

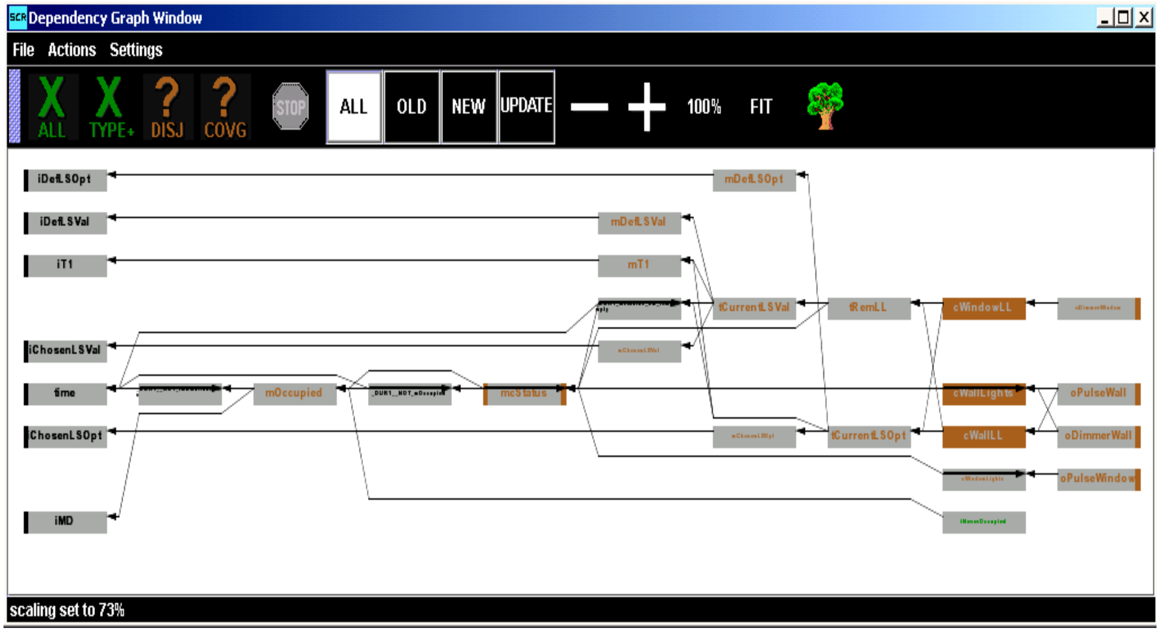
Deleted: wall AND tRemLL > 5000",¶ "

Deleted: wall AND tRemLL <= 5000",

Deleted: tRemLL - 5000","

Figure 5-8. A comparison of two SCR specifications, used to identify critical vertices. The comments show deletions; differences are underlined text.

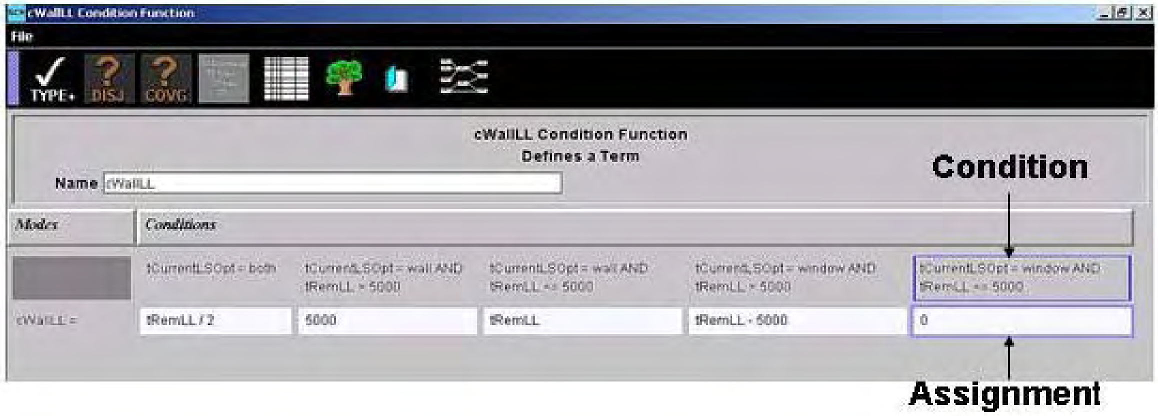
In this example, we see that condition functions *c*WallLL and cWindowLL differ; event function *c*WallLights also differs. Thus cWallLL, cWindowLL, and CWallLights define the critical vertices as shown by Figure 5-9.



scaling set to 73%

Figure 5-9. The scenario subgraph showing three critical vertices highlighted (darkened).

The SCR tool can display more detailed information about a critical vertex. For instance, the control parameters and output assignments for critical vertex cWallLL are shown by Figure 5-10.



cWallLL Condition Function
Defines a Term

Name cWallLL

Modes	*Conditions*				
	tCurrentLSOpt = both	tCurrentLSOpt = wall AND tRemLL > 5000	tCurrentLSOpt = wall AND tRemLL <= 5000	tCurrentLSOpt = window AND tRemLL > 5000	tCurrentLSOpt = window AND tRemLL <= 5000
cWallLL =	tRemLL / 2	5000	tRemLL	tRemLL - 5000	0

Figure 5-10. The conditions and assignments defining cWallLL.

Three Model Projections

Complex systems are multidimensional; thus, multiple projections (perspectives) are needed. The problem of determining the proper projections for this research is addressed by a simple partitioning of the system into the inputs and the outputs. We used these partitions to define three projections for a given subgraph: 1) the all dependencies projection; 2) the input projection; 3) the output projection.

The first projection named all, views all dependencies for a given subgraph. The input projection views all descendents; the output projection views all ancestors. For example, Figure 5-11 depicts a critical-vertex subgraph of the critical vertex *m*DefLSOpt.

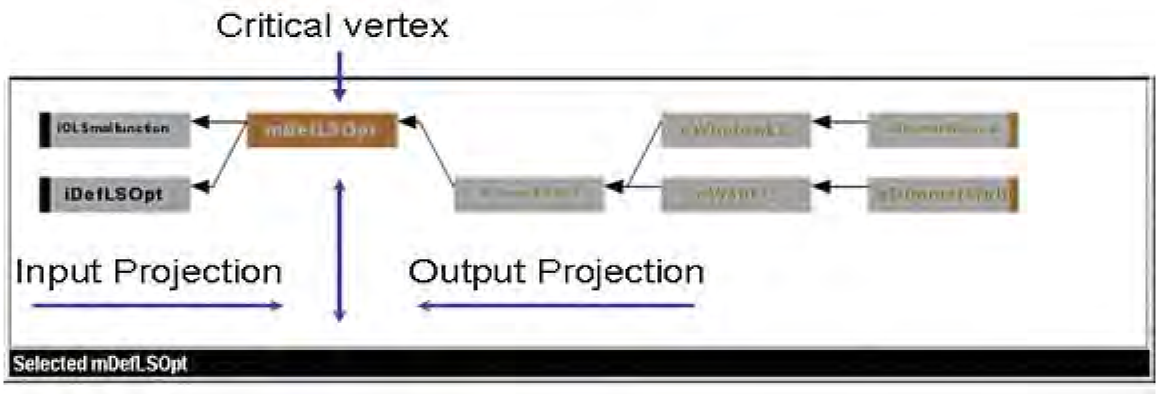


Figure 5-11. The critical-vertex subgraph abstraction for vertex mDefLSOpt.

The input projection affords a view of dependencies with respect to inputs. We see in Figure 5-11 that *m*DefLSOpt depends on two input vertices. Input vertices can change values when environmental input conditions change or when users use the GUI to change input parameters. For this example, the value of variable *i*OLSmalfuntion is determined by a sensor malfunction; the value if variable *i*DefLSOpt is set by a human using a GUI. The output projection enables a view of dependencies with respect to the outputs. We see in Figure 5-11 that the critical vertex is a descendent of two output vertices as well as three intermediate vertices.

The all projection looks at all dependencies associated with a given subgraph. In the case of Figure 5-11, the all projection includes all dependencies of critical vertex *m*DefLSOpt.

In summation, the input project enables a view of which inputs will affect the critical vertices while the output projection enables a view of the outputs affected by the critical vertices. The all projection is a collective view of all dependencies

Scenario Subgraph Metrics

The four metrics associated with the scenario subgraph are listed by Table 5-3.

Table 5-3. Coarse-grained metrics for the scenario subgraph abstraction.

Metric	Independent variable	Projection
Cyclomatic complexity	*X1*	all
Output cyclomatic complexity	*X2*	output
All paths	*X3*	all
Graph degree	*X4*	all

Each metric is described as follows:

X1 Cyclomatic complexity: McCabes cyclomatic complexity is calculated for the entire scenario subgraph. The subgraphs are weakly connected because dependency graphs are not connected from the output vertices to the input vertices. Adding a virtual edge from the output to input vertices will make the graph strongly connected (Vakil, 2000). Cyclomatic complexity is calculated as:

$$V(g) = e - n + (t + 1) \quad \textbf{(5-3)}$$

where:

e = number of edges
n = number of vertices
t = number of output vertices

X2 Output cyclomatic complexity: This metric is an indicator of the common-mode connectivity of the output vertices. For instance, the output vertices of Figure 5-12 have common-mode connections because each output vertex is connected to the same input vertex.

The process to determine X2 begins by creating a subgraph for each output vertex. The subgraph is output vertex induced where the vertices are descendents of a single output vertex. *X2* is the summation of cyclomatic complexities for each subgraph as calculated by equation 5-2.

$$X2 = \sum_{1}^{n} \mathrm{V}\ (\mathrm{g})\ n \qquad \textbf{(5-4)}$$

where:

n = number of output vertices
V (g) n = cyclomatic complexity of the subgraph induced by the descendents of output vertex n.

For example, Figure 5-12 is a graph with two output vertices *v2* and *v5* and a cyclomatic complexity of 4 as calculated using the "all" projection. We now calculate output cyclomatic complexity by using the "output" projection. Figure 5-13 is a subgraph of Figure 5-12. The subgraph is induced by the output vertex *v2*; the cyclomatic complexity is three. The subgraph induced by output vertex *v5* is similar, and has a cyclomatic complexity of three. Thus, using Equation 5-4, the output cyclomatic complexity *X2* is six.

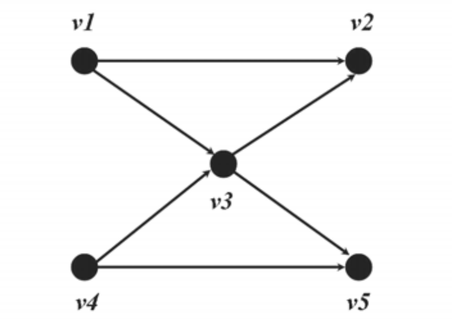


Figure 5-12. A graph with two output vertices and a cyclomatic complexity of four, and an output cyclomatic complexity of six.

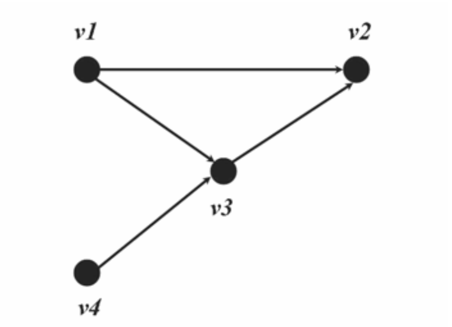


Figure 5-13. A subgraph of Figure 5-12 as induced by output vertex *v2*. The cyclomatic complexity is three.

Figure 5-14 is another example; note that the graph has the same number of vertices and it also has two output vertices. The cyclomatic complexity is 4 and is the same as Figure 5-12. However, we see that output vertices do not have common-mode connections so the cyclomatic complexity does not serve to measure the common-mode connections for output vertices. The output cyclomatic complexity Figure 5-14 is two; a significant reduction as compared to Figure 5-12.

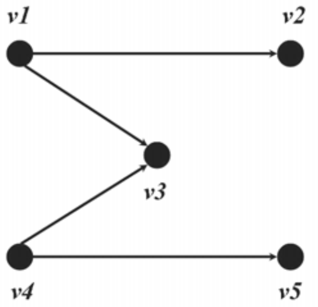


Figure 5-14. A graph with two output vertices and a cyclomatic complexity of four, and an output cyclomatic complexity of two.

X3 All paths: the maximum number of different directed paths. Each directed path begins at an input vertex and ends at an output vertex. Additionally, each directed path must not be a strict semipath.

X4 Graph degree: the total number of graph edges because it equals the sum of all edges into and out of each vertex.

Critical-state Subgraph Metrics

The five metrics associated with the critical state subgraph, listed by Table 5-4, are considered medium-grained metrics.

Table 5-4. The medium-grained metrics from the critical-state subgraph abstraction.

Metric	Independent variable	Projection
Critical state changes	*X5*	all
In-degree	*X6*	input
Out-degree	*X7*	output
Cyclomatic complexity	*X8*	all
Sheppard complexity metric	*X9*	all

*X*5 C*ritical-state changes:* The critical-state subgraph is used to determine this metric. This metric indicates the number of nonlinear branching or interconnections where *X5* is the number of variables that change for a single change of an input variable. Figure 5-7 serves as an example where *X5* = 9.

*X*6 *In-degree:* The value of *X6* is the summation of all edges going into the critical state subgraph vertices. For example, *X6* = 9 for Figure 5-7. The *X6* metric is from an input projection because looking from input to output vertices, we first encounter edges going into vertices.

*X*7 *Out-degree:* The value of *X7* is the summation of all edges going out of the critical state subgraph vertices. For example *X 7* = 9 for Figure 5-7. The *X7* metric is from an output projection because looking from output to input vertices, we first encounter edges leaving vertices.

X8 Cyclomatic complexity: Metric *X8* is calculated the same as metric *X1*. The difference is *X8* is calculated from the critical state subgraph.

X9 Sheppard complexity metric: Metric *X9* is a metric for interconnections where:

$$X9 = \left(X6 \text{ x } X7\right)^2 \qquad \textbf{(5-5)}$$

where:

*X*5 = out-degree; *X6* = in-degree.

Critical-vertex Subgraph Metrics

The six metrics associated with the critical-vertex subgraph are listed by Table 5-5. The metrics are described as follows:

Table 5-5. Fine-grained metrics from the critical-vertex subgraph abstraction.

Metric	Independent variable	Projection
In-degree	*X10*	input
Out-degree	*X11*	output
Sheppard complexity metric	*X12*	all
Input cyclomatic complexity	*X13*	input
Output cyclomatic complexity	*X14*	output
Vertex unique conditions	*X15*	all

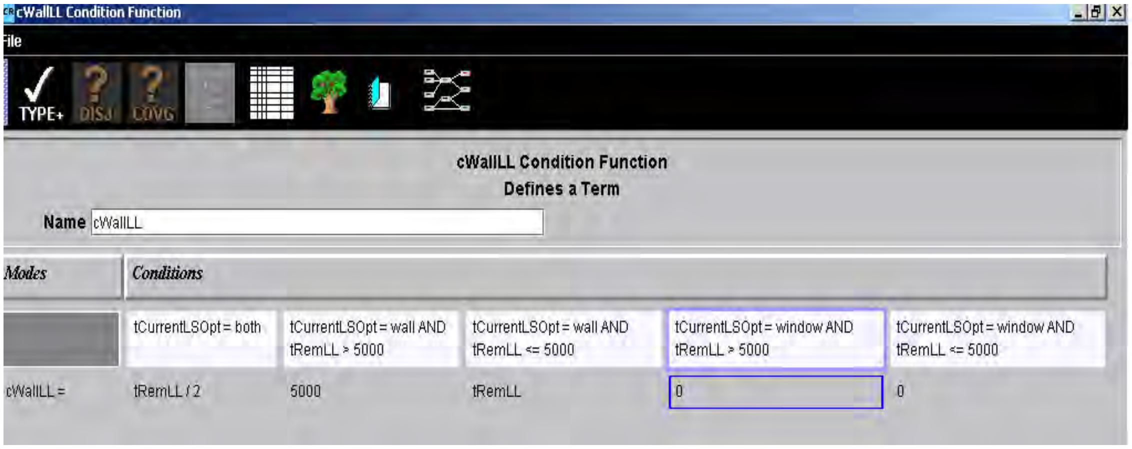
X10 In-degree; *X11 Out-degree*; *X12 Sheppard complexity*: The metrics *X10*, *X11*, and *X12* are calculated the same as metrics *X6*, *X*7, and *X9* respectively. Only the abstraction is different.

X13 Input cyclomatic complexity: The input projection is used to determine input cyclomatic complexity. The general process is the same as for the determination of output cyclomatic complexity. The input cyclomatic complexity is an indicator of common-mode connections for the input vertices.

X14 Output cyclomatic complexity: The metric is calculated by the same process used by metric *X2*. Only the abstraction is different.

X15 Critical-vertex conditions: Metric *X*15 is based on the SCR condition function. This is at the SCR specification level; therefore, it contains information that is not apparent with the dependency graph. Figure 5-15 shows the condition function for the critical vertex cWallLL. The value of cWallLL is based on meeting one of five conditions. For instance, "cWallLL=0" when the fifth condition "tCurrenLS0pt = window and tRemLL≤5000" is satisfied.

The *X15* metric is equal to the number of unique variable assignments. It is important that unique assignments are counted because programming style can distort the metric. Counting all the conditions of Figure 5-15 resulted in *X15* = 5. Notice that two assignments are the same value of zero. We can change the programming style by combining these two conditions into one condition. This results in four unique assignments for *c*WallLL; hence *X15* = 4.



cWallLL Condition Function

Defines a Term

Name cWallLL

Modes	Conditions				
	tCurrentLSOpt = both	tCurrentLSOpt = wall AND tRemLL > 5000	tCurrentLSOpt = wall AND tRemLL <= 5000	tCurrentLSOpt = window AND tRemLL > 5000	tCurrentLSOpt = window AND tRemLL <= 5000
cWallLL =	tRemLL / 2	5000	tRemLL	0	0

Figure 5-15. The condition function for the SCR term cWallLL. Four unique assignments for cWallLL are shown.

Summary

Chapter described a set of 15 metrics that were proposed as measures or indicators of three NAT complexity attributes. These NAT attributes were system interconnectivity, command-mode connectivity, and control parameter interactivity. The metrics of these NAT attributes are based on graph-theoretical measures of SCR dependency graph nonlinearity.

Complexity is multidimensional; therefore, multiple metrics system abstractions, and system projections were used. Three abstractions of SCR system dependency graphs were used; three system projections were used for each system abstraction. These projections were based on the external view of the system's inputs, outputs, and a view of all dependencies; thus, a hierarchy of system abstraction and projections were used for the set of 15 metrics proposed in this chapter.

Literature Cited

Gove, P. B. (Chief Editor). (1996). Webster Third New International Dictionary. Merriam Webster Inc.

Perrow, C. (1999). Normal Accidents: Living with High-Risk Technologies. Princeton, NJ: Princeton University Press.

Vakil, S. S. Analysis of Complexity Evolution Management and Human Performance Issues in Commercial Aircraft Automation Systems. Unpublished doctoral dissertation, Massachusetts Institute of Technology, Massachusetts Institute of Technology.

CHAPTER 6
RESEARCH VEHICLE: THE LIGHT CONTROL SYSTEM (LCS)

The LCS is a formalized system originally used to for requirements engineering seminars. It is a moderately complex, real-world system that includes human-computer interaction and safety requirements for normal and abnormal conditions.

The system is described in detail; this includes system functions, graphical user-interface, and modifications to the system to correct a safety hazard and three ‘bugs” in the original specification uncovered in this research. Additional modifications were made to create six versions of the system needed for the research design described in the next chapter.

Background

The LCS was devised by the Fraunhofer Institute for Experimental Software Engineering in Kaiserslautern (Queins et al., 2000) for a seminar on Requirements Capture, Documentation and Validation. The seminar was organized by E. Börger (Universita di Pisa, I), B. Hörger (Daimler-Benz, Ulm, D), D. Parnas (McMaster University, CAN), D. Rombach (Universität Kaiserslautern, D), with the objective to compare different approaches for requirements elicitation and specification. The LCS case study was used by the seminar as a vehicle to compare various requirements engineering methods. The results were published in a special issue on Requirements Engineering for the Journal of Universal Computer Science (Maurer, 2000).

The LCS specification, listed in Appendix A was based on the original version created in 1995, and a subsequent 1999 version used in an earlier seminar on

Requirements Capture, Documentation, and Validation. The LCS specification created for the 2000 seminar contains various improvements and refinements. The LCS specification takes the form of an informal requirements document as created by the customer. The requirements described functional requirements - the interactions between the environment, humans, and the hardware/software of the system. The requirements also state nonfunctional requirements - the constraints for the system such as timing and performance restrictions.

System Description

The LCS was formulated as a moderately complex, real-world system to control the interior lighting of a building consisting of various offices, laboratories, hallways, and staircases. The system's purpose is to efficiently control ambient lighting and to maintain a safe environment. Seven requirements specifically concern safety aspects for normal and abnormal conditions. For the purposes of this research, the control targets a single office. The control other offices and laboratory spaces would be identical.

The operation of the LCS is detailed in the test subject instructions of Appendix E. Briefly, the LCS controls light near the window and a light mounted near the wall. The control enables the user to set two light scenes named occupied and vacant:

- Occupied light scene: Automatically maintains a user-defined lighting intensity and configuration when the office is occupied.
- Vacant light scene: Automatically provides a user-defined light intensity and configuration when someone enters the office after the vacant light scene time delay has expired.

Lastly, the LCS provides manual lighting control: Manual pushbuttons enable on/off control of the lights. The manual controls enable users to over-ride the LCS

The LCS configuration for a single office is depicted by Figure 6-1. The system components consist of sensors, a logic solver, wall and window light actuators, and a user-interface panel. Five sensors are used; a motion sensor detects an occupied or vacant office; an analog sensor measures natural light in the office; a door closed contact indicates the door is open or closed; two status-line sensors indicate if the lights are turned on or off. The logic solver is PC-based and it provides control functions and a user-interface. Pushbutton switches enable manual and independent control of each light.

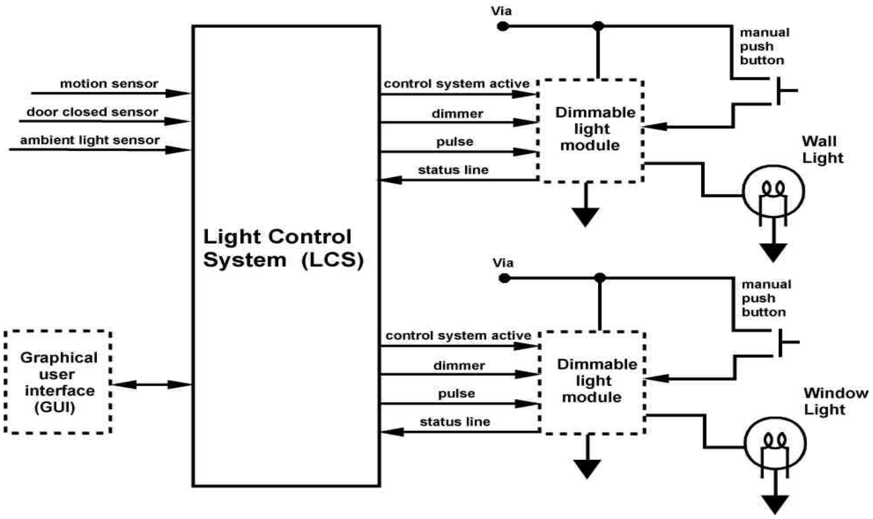
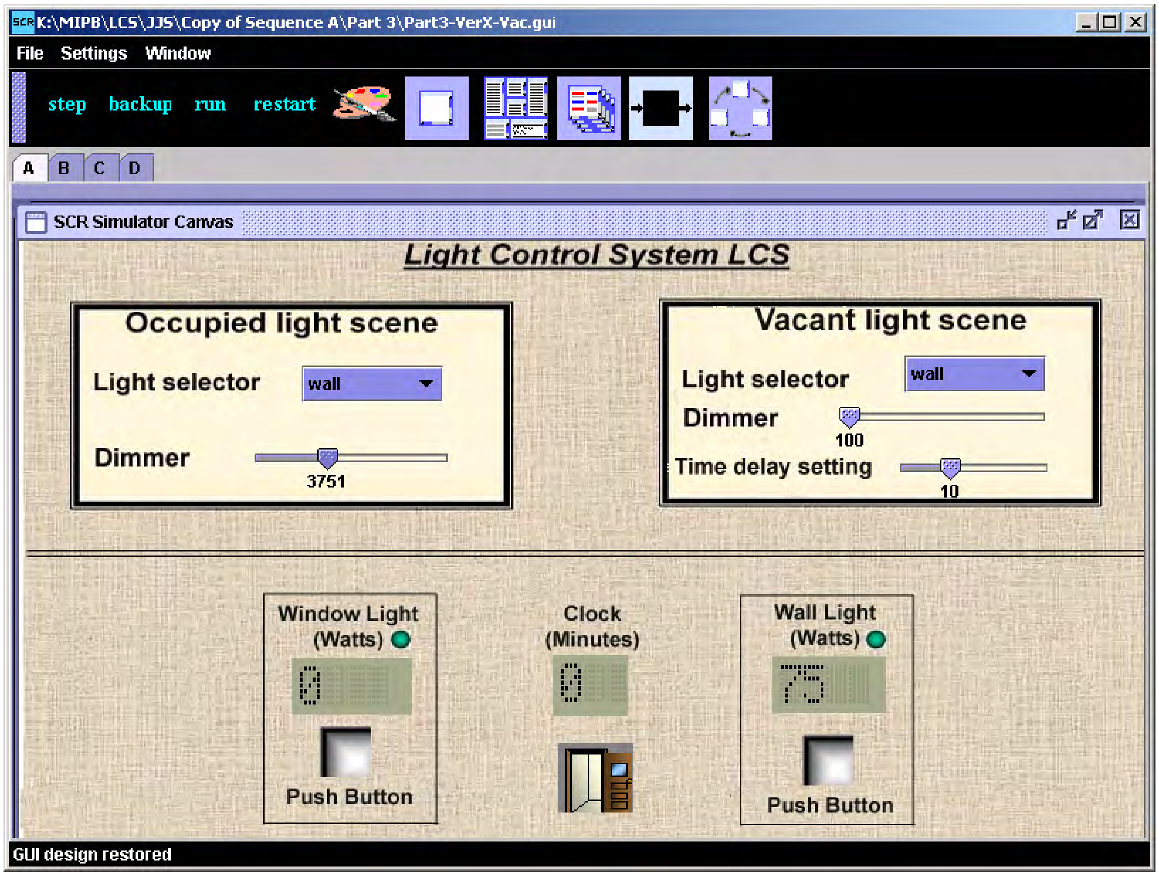


Figure 6-1. The Light Control System block diagram.

The LCS User-Interface

The PC-based user-interface, depicted by Figure 6-2, is used to set lighting scenes and display system information. The user selects the lighting configuration (wall, window, or both) and dimmer levels for the occupied and vacant light scenes. The user also sets the time delay associated with the vacant light scene. The following status information is displayed:

- Digital displays show the output for each light. No light is produced at 0 watts output; the maximum light is produced at 100 watts output.
- A digital displays shows elapsed time.



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Light Control System LCS

Occupied light scene

Light selector: wall

Dimmer: 3751

Vacant light scene

Light selector: wall

Dimmer: 100

Time delay setting: 10

Window Light (Watts): 0

Clock (Minutes): 0

Wall Light (Watts): 75

GUI design restored

Figure 6-2. The graphical user interface for the Light Control System.

The researcher created the user-interface by using the SCR simulator's object palette. Custom graphics for the door icons, background, and pushbuttons were created using Photoshop. Multiple refinements of the user interface resulted from pilot testing, described in chapter 7, and from reviews by NIOSH human factors researchers.

SCR Specification Modifications

The LCS requirements were written as an SCR specification and obtained from the Naval Research Laboratory (NRL). The SCR specification file dinreqdout.ssl was NRL's version 1.7 modeling the non-ideal LCS behavior (Heitmeyer & Bharadwaj, 2000) and is listed in Appendix B. This version of the specification served as the starting point for this research. The researcher modified the NRL SCR specification to correct three undesirable behaviors found in the version 1.7 specification, and to obtain the required behaviors for the test scenarios of this research.

The new SCR specification of this research consists of 15 monitored variables, 28 terms, eight controlled variables, one mode class, 24 conditioned functions, and 12 event functions; thus, it was a moderately large specification.

The researcher's SCR specification modifications included two new output variables named oWallOutput and oWindowOutput, were added to reduce system complexity by mitigating inferential information for wall and window light outputs. Perrow describes inferential information as a characteristic of a complex system. For instance, the original SCR specification uses variable oDimmerWall to represent the wall light intensity where zero watts gives no light and 100 watts gives maximum light. When oDimmerWall equals 100 watts, it infers that light is producing the maximum light output. However, the actual wall light output could be 0 watts. The oDimmerWall data is inferential because important information is missing; specifically, the pulse signal status as shown in Figure 6-2.

Each light is controlled by a dimmable light module that receives lighting demand intensity from the dimmer input, and receives a pulse input enabling the light to be turned off or on. The pulse is represented by the SCR variable oPulseWall. Therefore, if oDimmerWall equal 100watts and oPulseWall equals 0 watts, no light is produced; if oDimmerWall equals 100 watts and oPulseWall equals 1, and then light is produced.

Evidence of user confusion surfaced during LCS pilot testing. The pilot test GUI used a virtual 4-digit LCD to show the values of oDimmerWall and oDimmerWindow. The GUI also displayed on/off indicator lights for oPulseWall and oPulseWindow. The research observed that some pilot test subjects focused on the LCD's and did not observe the state of oPulseWall or oPulseWindow indicator lights. For instance, pilot test subjects found the externally visible behavior of the wall and window lights during the wall and window light pushbutton scenario to be very confusing. This scenario used the manually operated wall and window light pushbuttons to override the LCS control of lighting. Users could manually shut off the wall or window light even though the LCS was controlling the light at the desired intensity. The source of confusion is rooted in the interrelationships between the manual pushbuttons and the variable pairs oDimmerWall and oPulseWall, and oDimmerWindow and oPulseWindow. Table 6-1 summarizes the nature of the relationships between oDimmerWindow, oPulseWall and the wall light pushbutton. The relationships are identical for oDimmerWindow, oPulseWindow and the window light pushbutton.

Table 6-1. Actual light output with respect to pulse and dimmer signal values.

Wall light pushbutton state	oDimmerWall	oPulseWall	Actual wall light output
Off	100	0 (off)	0
Off	100	1 (on)	100
On	100	1 (on)	0

The actual wall light output is 0 regardless of the dimmer value specified by oDimmerWall when the pulse signal oPulseWall is in the off state. Note also oDimmerWall is independent of signal oPulseWall; this also caused user confusion because pilot test subjects expected the dimmer value to equal zero if the pulse value was zero. Therefore, the researcher created new variables, oWallOutput and oWindowOutput, to represent the actual light output values. This eliminated subject confusion during pilot test by using the same virtual 4-digit LCD to display the values of oWallOutput and oWindowOuput on the GUI.

The researcher discovered a safety issue with the specified LCS behavior, and three bugs with the NRL specification. These were discovered during the process of executing the complexity assessment methodology of this research.

The safety issue concerns the fault tolerance requirement NFI, section (3.2.1.) of the LCS problem description. This requirement can put the LCS in a state that creates a hazard to the building's occupants. Specifically, the requirement is for the LCS to use the last known good datum from ambient light level sensor if the LCS detects a malfunction of this sensor. This behavior causes a hazard because people could enter a dark office without the lighting coming on. This hazard occurs when the ambient light sensor malfunctions during very bright ambient light levels where the naturally occurring light provides all the lighting requested by the user; thus, the wall and window lights are reduced to 0 watts output. The specified behavior during the malfunction causes the system to use this high light level because it was the last known value before the malfunction. Hence, users entering an office at night after a malfunction has occurred during these high level lighting conditions will find the office dark because the LCS system believes ambient light is providing all the lighting needed. The researcher collaborated with experts from the NRL to correct this problem. The first correction was to modify the indoor lighting level monitoring function so that it assumes it is dark outside in the case of a malfunction lighting sensor. This essentially would be a failsafe state because lighting would always be available. The second fix to this problem was to have the ambient light sensor re-read after an ambient light sensor malfunction so that the latest reading can be used. Without this, the value before the failure would remain in the system until the sensor reading changed again and the malfunction was cleared.

The three bugs with the SCR specification are not safety related but, do cause undesirable behavior that could confuse the occupants of the building. The first and second problems are related to the initial state of the system. The third bug concerns the ambient light level sensor.

The first problem concerns the light status of the room when someone first enters the room. The LCS problem description specified that upon the first time a room is entered that the default light scene should be on. This did not occur during the execution of the LCS specification by NRL. The second problem is also related to this initial state. This problem however does have safety implications. Under the right conditions, the LCS control system would shut off all the lights in the office even though the office was occupied and lighting was called for. The system will erroneously go to an unoccupied state two minutes after a person enters an office for the first time. At this point, the system is in a temporarily empty state classification. Therefore a timer associated with the temporary empty state begins counting, and once this timer elapses, the lighting will be shutoff to the office even though an operator or a user is in the room. The third problem that occurs is that the current dimmer outputs do not correctly account for the natural light entering the room for any given state.

Again the researcher collaborated with NRL personnel to correct these three problems. At this point, this brings us to the SCR specification, designated as treatment A, containing the corrections for the three NRL bugs and the undesirable safety behavior specified in the LCS specification.

Scenario Descriptions

Three scenarios were designed to exercise all of the major LCS functions. More importantly, the scenarios are based on LCS behavior the researcher found to exhibit NAT characteristics of confusion, transparency, and unpredictable system behavior. Therefore, the researcher began with the complex system, designated as treatment A, then simplified the system and designated this as treatment B. Two treatments are needed to test the research hypotheses. The next chapter details the research methodology for treatments A and B.

The Vacant Light Scene Scenario

The vacant light scene is used to maintain safety and save energy. It provides a minimal lighting level when a user enters an office. The scene helps save energy by reducing the lighting once the office has been vacated for longer than a user-defined time delay; therefore, if a person does not shut off the lights when leaving the office, the LCS will automatically reduce the lighting level once the time delay expires. The vacant light scene settings are defined and set by the user

Appendix E contains the detailed subject instructions for the vacant light scene scenario. Subjects are instructed to set the vacant light scene to the window light at 20 watts, with a time delay of five minutes. After the scene is set, the subject leaves the office, and advances time from zero to seven minutes while watching the state of the vacant light scene. The subject reoccupied the office at seven minutes and observed the vacant light scene settings.

The vacant light scene scenario for treatments A and B is summarized by Table 6-2. The items of primary interest are in bold. The first critical time is at five minutes, the time delay setting. Note that the LCS behavior for treatments A and B are identical up to the time delay setting of five minutes. The vacant light scene activated at five minutes and remained activated for treatment B, the less complex system. Therefore, the vacant light scene was on when the subject reoccupied the office. The behavior for treatment A differed in that the vacant light scene did not activate until the subject re-entered the office at seven minutes.

Table 6-2. Vacant light scene scenario values for treatment A and B. The items of primary interest are in bold.

Time (Minutes)	LCS Mode	Light Scene	Treatment A Vacant Light (Window)	Treatment B Vacant Light (Window)
0	occupied	occupied	disabled	disabled
1	temp. empty	occupied	disabled	disabled
2	temp. empty	occupied	disabled	disabled
3	temp. empty	occupied	disabled	disabled
4	temp. empty	occupied	disabled	disabled
5 (delay time value)	**temp. empty**	**vacant**	**disabled**	**enabled @ 20 watts**
6	temp. empty	vacant	disabled	enabled @ 20 watts
7	**occupied**	**vacant**	**enabled @ 20 watts**	**enabled @ 20 watts**

The Lighting Options Scenario

This scenario demonstrates the operation of the lighting options. The lighting options are wall lights, window lights, or both lights. The lighting options are selected by the user. Appendix E contains the detailed subject instructions for the lighting options scenario.

Section 4 is the dictionary of terms for the LCS requirements. The operation of each lighting option is defined within the definition of the light scene term. The light scene definition follows; italics were added for emphasis:

> A light scene is a predefined setting of the ambient light level and a description that determines in which way the ceiling light groups should be used to achieve this ambient light level. A light scene is given by:
>
> 1. name of the light scene
> 2. the desired ambient light level in a room
> 3. one of the following three options: window, wall, or both
>
> Window means that at first the ceiling light group near the window should be used to achieve the desired ambient light level and then the other ceiling light group.
>
> Wall means that at first the ceiling light group near the wall should be used to achieve the desired ambient light level and then the other ceiling light group.
>
> Both means that both ceiling light groups should be used equally to achieve the desired ambient light level (Queins et al., 2000).

If the requested level of light can not be supplied by a single light, then the LCS automatically supplies power to the other light in order to meet the request. Each light provides up to 100 watts. So, if the wall light is selected, and the requested light level is 150 watts, then the LCS automatically controls the window light to provide 50 watts, even though the user requested only the wall light. The outputs for treatment A are listed by Table 6-3, and depict the situation when the dimmer is set to 7,500. Treatment B differs by not automatically shifting part of the lighting demand to the window light.

Table 6-3. Lighting options scenario values for treatment A and B. The items of primary interest are in bold.

Dimmer Settings		Treatment A		Treatment B	
Wall	Window	Wall Output (Watts)	Window Output (Watts)	Wall Output (Watts)	Window Output (Watts)
0	0	0	0	0	0
2,500	0	50	0	50	0
5,000	0	100	0	100	0
7,500	**0**	**100**	**50**	**100**	**0**
10,000	**0**	**100**	**100**	**100**	**0**
7,500	**0**	**100**	**50**	**100**	**0**
5,000	0	100	0	100	0
2,500	0	50	0	50	0
0	0	0	0	0	0

The Wall and Window Light Pushbutton Scenario

This scenario demonstrates the operation of the light pushbuttons. The manually operated wall and window light pushbuttons are used to override the LCS. Manual override of the LCS control occurs when the window pushbutton state is “on.” Appendix E contains the detailed subject instructions for the wall and window light pushbutton scenario.

Requirement 2 of section 2.1 of the LCS problem description, defines the behavior for the pushbuttons. It states:

> Each office is equipped with:
>
> 1. one motion detector (imd), so that the room is fully covered.
> 2. two ceiling light groups (window and wall).
>
> The luminaries in a ceiling light group in any room are turned on or off only as a group. Each ceiling light group is controlled by one push button on the wall (pb1 and pb2, respectively), which toggles the ceiling light group if pushed.
>
> A ceiling light group in a room shows the following behavior if the corresponding push button is pushed:

(i) if the ceiling light group is completely on, it will be switched off

(ii) otherwise it will be switched on completely (Queins et al., 2000).

Table 6-4 depicts the operation of the window light pushbutton for treatments A and B. Note that both treatments behave identically until the last table entry (in bold). Treatment A did comply with the specification although this is not intuitive; also, it does not follow the functional mental model most people have concerning a pushbutton switch found in homes and offices.

When the prior state is window output = 50 watts, the window light is not fully on. So, when the window pushbutton changes to the on state, the current state becomes window output′ = 100 watts. For treatment B, window output′ = 0 watts; this behavior follows the typical functional mental model for a pushbutton light switch.

Table 6-4. Wall and Window light pushbutton scenario outputs for treatments A and B. The items of primary interest are in bold.

Window pushbutton	Treatment A		Treatment B	
	Window output (Watts)	Window output′ (Watts)	Window output (Watts)	Window output′ (Watts)
off	0	0	0	0
on	0	100	0	100
off	100	100	100	100
on	100	0	100	0
off	50	50	50	50
on	**50**	**100**	**50**	**0**

Note: Window output′ is the current state value while window output is the prior state value

Summary

The research test vehicle is the LCS, a formally documented system used as a case study for requirements engineering seminars. The function behavior of the LCS was described as well as the GUI created for human interaction with the LCS. This research modified the LCS behavior to mitigate a safety hazard and three bugs in the original LCS as constructed as an SCR specification. Next, the LCS specification was modified to generate two treatments for three scenarios named the vacant light scene, the lighting options scenario, and the wall and ceiling light push button scenario. Treatment A of these scenarios follows the LCS specifications. Treatment B is made to be more intuitive and to match typical functional mental models. The treatments and scenarios are used to test the research hypotheses. The next chapter explains how these treatments and scenarios are used in the research methodology.

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CHAPTER 7
RESEARCH METHODOLOGY

This chapter describes the specific tasks, sequences, and research methodology needed to realize the research objective: to develop a complexity assessment methodology for system requirements of safety-related e computer systems by operationalizing NAT.

A multiple data source approach was taken to increase construct validity. The research included the use of the Discount Usability Engineering method to evaluate system usability, and a crossover research design to obtain multidimensional data from two sources: a questionnaire instrument for the test subjects and observer notes

Thirty-two convenience subjects from the NIOSH Pittsburgh Research Laboratory used PC-based simulations of the LCS described in chapter 6. The subjects were randomly assigned to execute scenarios that used the main functions of the LCS. The nine-part questionnaire instrument of Appendix D was used for the collection of dependent variable data. Three dependent variables were measured using a five-point Likert scale.

Lastly, six subjects were used to conduct pilot tests. This resulted in improvement and refinement of the subject instructions and the GUI; specifically, the instructions were shorter, easier to follow, and easier to understand; the GUI was simplified to make it more intuitive.

Experiment Overview

This experiment consisted of two major parts having a total of six steps. The first part was to teach subjects about the LCS. This was achieved in three steps:

- Watch a short instructional video concerning the operation of the LCS;
- Read a description of the GUI and the operating instructions for the LCS;
- Receive "hands-on" training by using the basic LCS functions during a 10minute warm-up session.

For the second part, the subjects:

- Followed a one page set of instructions to run a scenario;
- Answered the questionnaire after running each scenario;
- Take a one-minute break after running each scenario.

Research Design

The research used the Discount Usability Engineering method to evaluate the usability of the LCS. The usability was evaluated for a warm-up session and six scenarios of LCS operation.

The research design uses a crossover design. The main advantages of using standardized designs and methods are pre-established validity and a prior knowledge of strengths and limitations.

Discount Usability Engineering

The Discount Usability Engineering method was used to evaluate system usability: one of our dependent variables. A strong point of this method is that it can maximize data significance given small sample population sizes. Nielsen's research shows that three to five subjects achieves the maximum benefit-cost ratio for this method (Nielsen, 1994). Secondly, the method's simplicity was an advantage. It was much less likely that error and biases are introduced from misapplication of complex methods.

The Discount Usability Engineering method uses three techniques: scenarios, simplified thinking aloud, and heuristic evaluation. A scenario contains a set of events, tasks, and operations typically encountered in the system operation. A scenario can consist of normal or abnormal situations. The simplified thinking aloud technique encourages the subjects to vocalize their thoughts as they perform typical tasks. Researchers record these thoughts and encourage the users to vocalize their thoughts and provide user feedback.

A crossover design was used to compare difficult and easy scenarios using within subject comparisons and allowing for multiple evaluations per subject. This research design is commonly used for clinical drug studies.

Crossover Design

The crossover design has a significant advantage because the subjects serve as their own control. The other advantages include greater sample size efficiency with randomization of treatment order and all subjects receive all the treatments. The basic structure of a crossover design is depicted by Figure 7-1. Randomly, half of the subjects received treatments in a given order while the other half received the same treatments in reverse order. A washout or waiting period was established between treatments to minimize carryover or residual learning effects from the prior treatments. The washout duration varies with respect to the specific study. For example, drug studies could have washout periods ranging from hours to days depending upon how quickly a drug leaves the bloodstream. Lengthy or unknown washout periods are a disadvantage; however, the washout period used in this research was just a few minutes because the residual effects are not physiological. Short washout periods are needed because of practicality.

Specifically, there are six washout periods; therefore, the total time for washout periods was relatively short. Lengthy washout periods could otherwise confound data from fatigue or boredom.

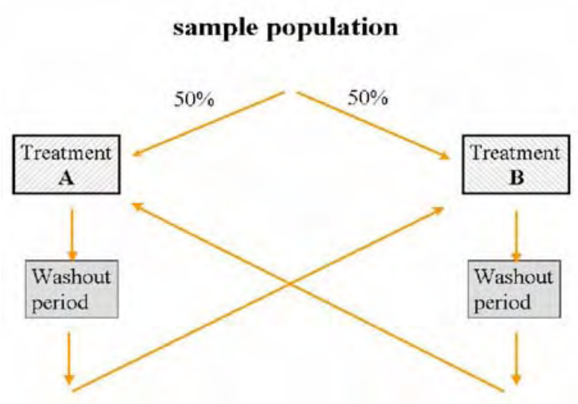

Figure 7-1. The basic structure of a crossover design consists of two treatments and two washout periods.

For this study, the basic crossover design structure was kept intact in that two treatments are used. We add three scenarios of LCS operation: the scenarios are a component of the Discount Usability Engineering method.

The experiments used two versions of the LCS to facilitate hypothesis testing. The first version, treatment A, was a complex version of the LCS; the independent variables were manipulated to increase NAT complexity. The second version, treatment B, had the independent variables manipulated to decrease complexity.

Each subject was given the same set of written instructions in order to establish experimental consistency. There was also a warm-up session to familiarize subjects with operation of the PC-based simulation.

The same set of scenarios was used for treatments A and B. After each scenario was completed, subjects answered the questionnaire of Appendix D, designed to elicit their perceptions of the system. The responses were assumed to depend on the assigned treatment.

Two structured test sequences of scenarios and treatments were used to establish known test patterns; one test sequence was used by half of the subjects and the other test sequence was used by the other half. The test sequences of scenarios and treatments were optimized for the crossover design (Jones & Kenward, 1998). Tables 7-1 and 7-2 list the test sequences with their associated scenarios and treatments. .

Table 7-1. Sequence 1 ordering of the scenarios and associated treatments.

Order	Scenario	Treatment
0	warm-up session	
1	washout period	
2	1	A
3	washout period	
4	2	B
5	washout period	
6	3	A
7	washout period	
8	2	A
9	washout period	
10	1	B
11	washout period	
12	3	B

Table 7-2. Sequence 2 ordering of the scenarios and associated treatments.

Order	Scenario	Treatment
0	warm-up session	
1	washout period	
2	3	B
3	washout period	
4	1	B
5	washout period	
6	2	A
7	washout period	
8	3	A
9	washout period	
10	2	B
11	washout period	
12	1	A

The two sequences were useful for detecting and limiting learning effects by reducing the potential learning effects to a subset of known scenario and treatment ordering. A totally randomized sequence of scenarios could potentially have a wider range of learning effects thus making it more difficult to address.

Internal Validity Threats

The research methodology was also designed to reduce potential threats to internal validity. Compromises of internal validity result in biases that cloud inferences concerning the observed effects that the independent variables may have on the dependent variables. Internal validity considerations included construct validity and unintended treatment effects. The following steps were made integral to the research to increase internal validity:

- *Construct validity:*
    - Used multidimensional data;
    - Used multiple data sources;
- *Unintended non-experimental effects (a.k.a. Hawthorn effect):* Independent observers were used to proctor tests and collect data

Warm-up Session

All subjects receiving treatments A and B conducted the same warm-up session prior to conducting the LCS test. The warm-up served as a hands-on practice session. The objectives of this session were to help subjects become familiar with running a scenario and become familiar with using the GUI. The subjects answered a set of questions concerning each of these objectives after they completed the warm-up session.

Test Sequence Summary

The test sequences are summarized using the appropriate statistical terminology as follows:

- *2 Sequences:* Tables 7-1 and 7-2 describe the sequences.
- *2 Treatments:* Treatment A (more complex), Treatment B (less complex)
- *3 Periods:* Scenarios 1, 2, 3 (each scenario was a set of typical user tasks)

Observers

Three volunteers from the NIOSH Pittsburgh Research Laboratory were test observers: they were used to administer the tests and collect data. The observers did not know the purpose of the research or understand the operation of the LCS. This was an intentional part of the design so as to reduce the potential for observer-induced biases. Observers took notes about each subject; the notes contained observations on the subject's verbal comments, actions, and body language during the test.

Subjects

The research includes the use of human subjects; therefore, the methodology required review by the West Virginia University Institutional Review Board (IRB) for the protection of human subjects. Due to the minimal risk of the tests, an exemption was requested and granted. Appendix C contains the exception request and IRB approval.

A total of 41 subjects from the NIOSH Pittsburgh Research Laboratory volunteered to participate in this study. Six of these subjects participated in pilot testing; 32 subjects participated in the LCS tests; three served as test observers. All subjects were recruited as volunteers by word of mouth from researchers from NIOSH, Pittsburgh Research Laboratory.

Measurement Methods

Two methods are used to collect dependent variables: the think-aloud protocol of Discount Usability Engineering method and the questionnaire instrument of Appendix D.

Questionnaire Instrument

Table 7-3 maps the dependent variables to the specific questionnaire sections. Portions of the questionnaire are from two respected and validated instruments: the

Questionnaire for User Interaction Satisfaction (QUIS) and the Software Usability Measurement Inventory (SUMI).

Table 7-3. The dependent variables and corresponding sections of the questionnaire.

Dependent Variable	Questionnaire Sections
Predictability (*p*)	3.1.1, 3.1.2, 3.1.3, 3.2
Observability (*o*)	3.3.1, 3.3.2, 3.4, 3.5, 3.6
Usability (*u*)	3.7, 3.8, 3.9, 3.10

QUIS is used to "provide researchers with a validated instrument for conducting comparative evaluations, and serve as a test instrument in usability labs" (Human Computer Interaction Laboratory, 2002).

SUMI is "a rigorously tested and proven method of measuring *software quality* from the *end user's point of view*" and "as the de facto industry standard questionnaire" (Human Factors Research Group, 2002). The international standard ISO 9241 recognizes the SUMI method to test user satisfaction.

The validity of the QUIS and SUMI surveys was kept intact by using a two-step adaptation process. The first step "filters" for questions pertaining to this research. The second step "focuses" the questions explicitly to this research. For instance, a question with "this software" was reworded to "this system".

Each subject completes the questionnaire to elicit their perceptions. The questionnaire uses multiple choice and open-ended questions. The multiple-choice questions are based on a five-point Likert scale. Open-ended questions are used to collect post-experimental data for the experiment at the conclusion of the entire sequence.

Observer Notes

The think-aloud technique yielded qualitative data as recorded by an observer during subject testing. The data was recorded in the form of written observations of the subject's verbal and nonverbal communications during the tests. This qualitative data was another component assumed to be dependent on the treatment, adding another dimension to dependent variable data from the perspective of the observer.

Pilot Testing

The main objective of pilot testing was to identify and correct the weaknesses and shortcomings with the LCS instructions, test scenario instructions, and the graphical user interface (GUI) before conducting LCS tests with 32 subjects. Six convenience subjects volunteered to conduct pilot testing: these subjects did not participants in LCS tests.

The pilot testing proved to be very beneficial. It resulted revising the instructions to make them shorter and easier to follow and understand. It also resulted in a simpler, more intuitive GUI.

Subject Instructions

Subjects received written instructions for the operation of the LCS and for executing the tasks of each scenario. There was considerable variation in subject comprehension, subject errors, and with the expected subject actions and behaviors. Many instruction-related issues were found to be dependent on the form or method of delivering instructions. It was also evident that using written instructions alone would not suffice for a group of 32 subjects because of the variability in the way people learn. For instance, some people learn best by reading while others learn by listening; yet others learn by doing. Realistically, people learn in various combinations of these. Hence, instructions were delivered by multiple methods as described:

- *LCS instruction improvements:* The information was presented in four forms to accommodate subjects who learn by reading, watching, listening, and by doing. First, subjects watched a PowerPoint presentation having pre-recorded narratives. The presentation gave an overview of the process and the operation of the LCS, which also contained a video file of the researcher executing the warm-up sessions.

These provided a dynamic example of using the LCS GUI, and using the read-aloud and think-aloud techniques.

- *Scenario instruction improvements:* The researcher observed that errors of omission were predominant and that most subjects had difficult comprehending the scenarios. Subjects were merely following instructions so they did not closely observe or understand LCS behavior. Changing the instructions in two ways provided an improvement. The first was to rewrite the scenario instructions changing from a sequence of operator tasks to a set of instructions that establish an objective within the context of a story. Therefore, each instructed task had more meaning for subjects because they could place the tasks within the context of the scenario's objective.

- *Subject comprehension and errors of omission improvements:* It appeared that subjects were reading instructions too quickly. To remedy this, subjects were asked to read the instructions out loud. This activity slowed down and focused the subject's thoughts on the instructions. The researchers observed these benefits:

    - eliminated errors of omission;
    - improved subject comprehension;
    - increased subject vocalizations during the think aloud technique;
    - facilitated observer data collection because it was easier to follow and record subject observations;
    - facilitated observations because it gave observers an additional data source; for example, as the subject read the instructions, an observer could infer as source of confusion to be with the instructions.

The researcher's "read-aloud" technique was an effective solution for the scenario instruction issues, and it provided additional benefits. The read-aloud technique had merit for this research. Additional investigation into the effectiveness of the read-aloud technique is needed.

Graphical User Interface Improvements (GUI)

The original user interface grouped interface controls by categories. For instance, the dimmer slide controls were grouped together and the lighting option pull down menus were grouped together. Subjects found this cumbersome and non-intuitive.

The researcher's solution was to group interface controls by LCS functions. Specifically, the user interface groupings were the occupied light scene, vacant light scene, and window and wall light groups.

Data Preparation

Dependent Variables

Each dependent variable has a quantitative component: obtained from the subject questionnaire ratings, and a qualitative component: obtained from written observations of each subject during tests.

The raw dependent data for the three scenarios was entered from the questionnaire into a single Excel spreadsheet. Columns were also added for each dependent variable. These columns contained the mean subject ratings of predictability, observability, and usability for each subject.

Qualitative Data

Qualitative data was quantified by using a process of categorizing and mapping the data to a five-point Likert scale as used by the subject questionnaire. This process is depicted in figure 7-2. Once the observer data was quantified, the mean values for each category was weighted by 30%, then combined with questionnaire data for dependent variables *p, o,* and *u*.

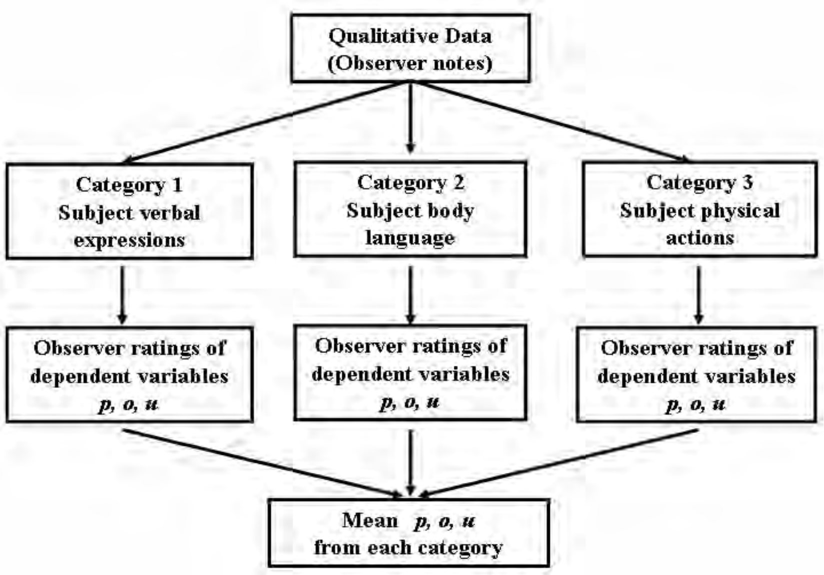
Qualitative Data (Observer notes)
Category 1 Subject verbal expressions
Category 2 Subject body language
Category 3 Subject physical actions
Observer ratings of dependent variables p, o, u
Observer ratings of dependent variables p, o, u
Observer ratings of dependent variables p, o, u
Mean p, o, u from each category

Figure 7-2. The process of quantifying qualitative data from observer notes.

Variable Naming Conventions

Dependent Variables:
Example: Y1AP = predictability variable for Treatment A of the vacant light scene.

- Position 1: Y = Dependent Variable
- Position 2: Scenario identifier where 1 = Vacant light scene, 2 = Lighting options, and 3 = Wall & window light push button scenario.
- Position 3: A = Treatment A (complex); B = Treatment B (less complex)
- Position 4: Category identifier; P = Predictability, O = Observability, U = Usability

Independent Variables:
Example: X1A1 = variable 1 for the Treatment A of the lighting options scenario.

- Position 1: X - Independent Variable
- Position 2: Scenario identifier where 1= Vacant Light Scene, 2= Lighting Options, and 3= Wall & window light push button scenario.
- Position 3: A = Treatment A (complex); B = Treatment B (less complex)
- Position 4: Sequential numeric identifier

Warm-up Variables:

- W1 - the mean value for the subject's ease of following and understanding the warm-up.
- W2 - the mean value for the subject's ease of using the GUI to run the warm-up.

Summary

The experimental method and plan were presented. The research design was based on a cross-over design; a standard design with an established validity. The research also used a standard usability evaluation method: the Discount Usability Engineering method. Our research methodology and plan addresses the test subjects, measurement methods, data collection and preparation, and the statistical analyses. Lastly, the threats to internal validity are recognized and addressed.

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CHAPTER 8
DATA ANALYSES AND HYPOTHESES TESTING

The previous chapter described the research methodology used to conduct tests. This chapter details the analysis of test data and the hypotheses testing. Descriptive statistics of median and mode, and histograms were used to characterize the test subjects, the results of warm-up tests, and the main test results. Next, data validity was addressed by analyzing subject data for outliers, by conducting data reliability estimates, and by investigating data trends for evidence of data confounding.

Once data validity was established, nonparametric statistical methods were used to test the hypotheses. Canonical correlation analysis and structure correlations were used determine what linear combination of dependent variables was most strongly correlated with a linear combination of independent variables. The results pertain to null hypotheses 1 through 3 − the dependent variables predictability, observability, and usability do not correlate with our NAT metrics of complexity. The Wilcoxon signed-rank test was used to test hypotheses 4 through 6 − increasing NAT complexity does not decrease system predictability, observability, and usability.

Lastly, the results of statistical tests were determined through the calculation of p-values, standard errors, and 95% confidence intervals.

Subject Profiles

Thirty-two volunteer subjects from the National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory participated in testing. The subjects had no prior knowledge or involvement of this research. Each subject responded to all questions for

Part 1 of the questionnaire instrument of Appendix D. The typical subject is characterized as follows based upon subject data collected during pre-test activities:

- 78.1% - technical job classification;
- 71.8% - 45-65 years old;
- 87.3% - male;
- 100% - no prior involvement in the research;
- 84.4% - no knowledge of the light control system test vehicle;
- 84.4% - PC experience rated at 4 or 5 (expert).

Figure 8-1. characterizes subjects in more detail. Each x-axis item represents a question from part 1 of the subject questionnaire of Appendix D.

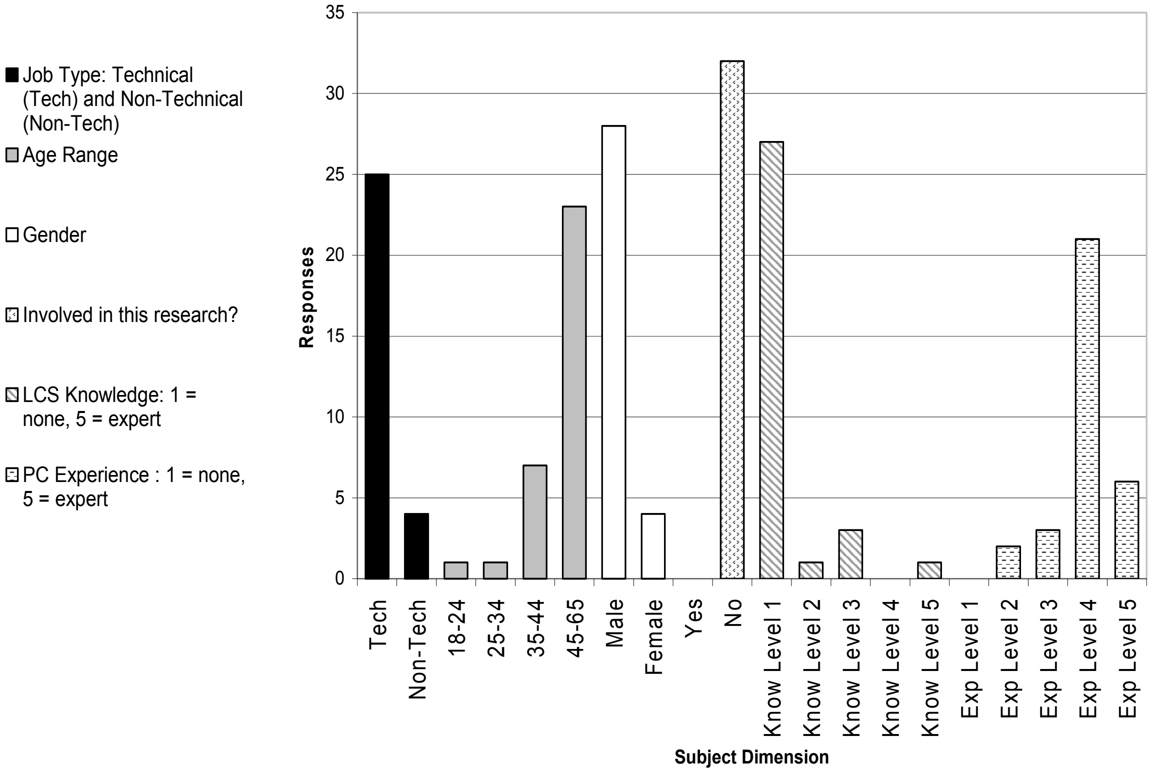

Figure 8-1 Subject profile data from the subject questionnaire of Appendix D.

Subject Responses for the Warm-Up Session

Two measurements were used to characterize the subject's perceptions of the overall warm-up session. W1 is a measure of the subject's ease of following and understanding the warm-up instructions. W1 was calculated as the mean of 28 subject ratings for questions 2.1.1 to 2.1.4 of the questionnaire. Figure 8-2(A) depicts the histogram for W1. W2 represents the subject's ease of using the GUI. W2 measures the subject's ease of using the GUI to run the warm-up. W2 was calculated as the mean of 28 subject ratings for questions 2.2 to 2.6 of the questionnaire. Figure 8-2(B) depicts the histogram for variable W2.

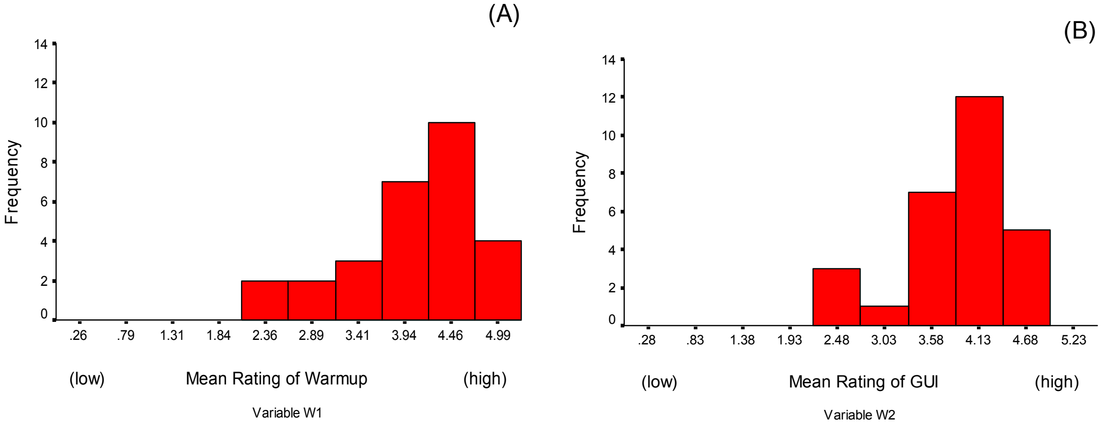

Figure 8-2. Mean subject responses for the warm-up session. Graph (A) depicts the subjects understanding of session tasks. Graph (B) depicts the subject's ease of using the GUI.

Test Data Characterizations

A more detailed depiction of subject responses is presented by a series of histograms. The frequency of responses for each scenario and treatment are depicted by the histograms of Figures 8-3, 8-4, and 8-5

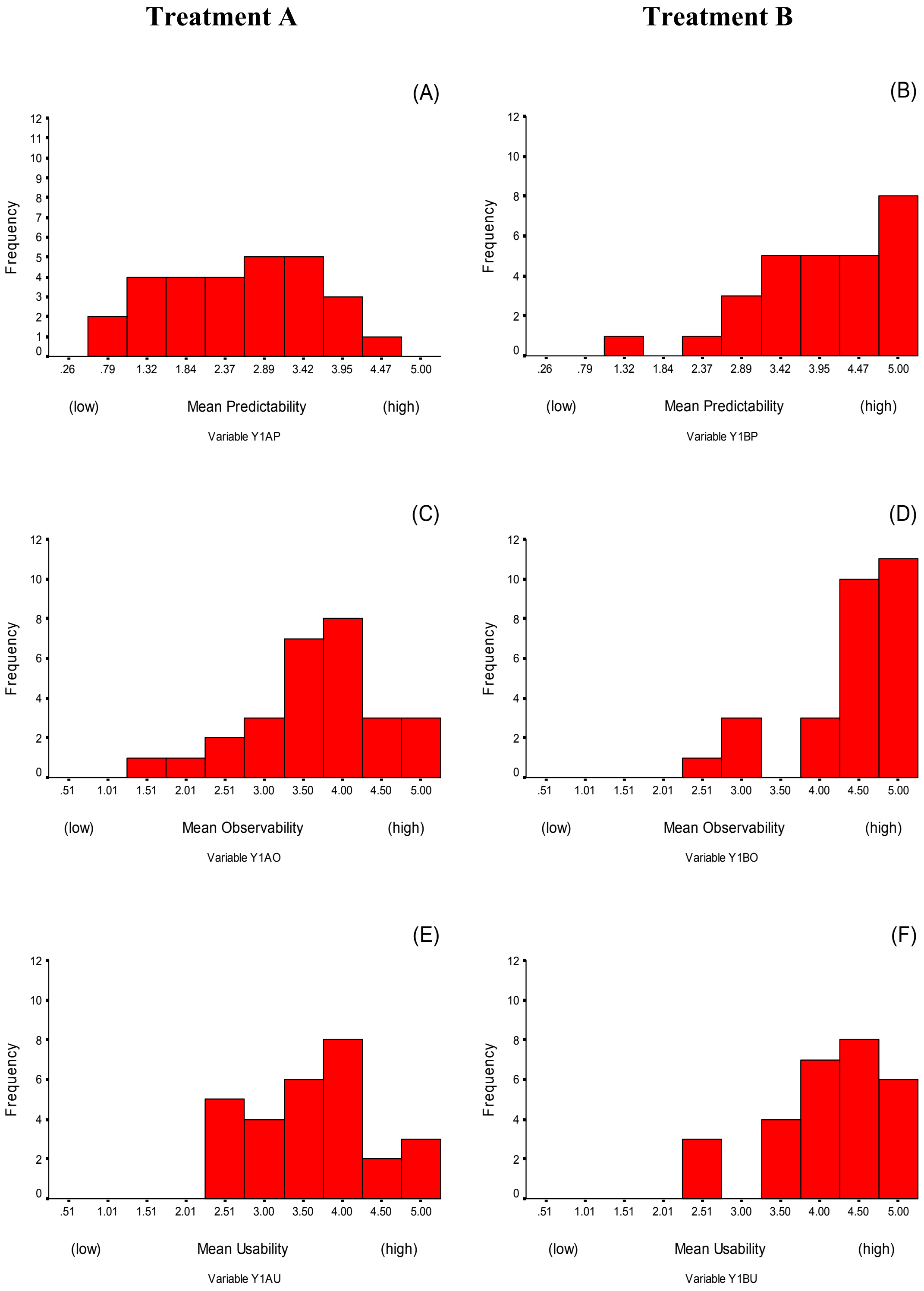

Figure 8-3. The mean predictability, observability, and usability responses for the vacant light scene scenario. Graphs (A), (E), and (D) depict treatment A responses; graphs (C), (B), and (F) depict treatment B responses. N = 28 subjects.

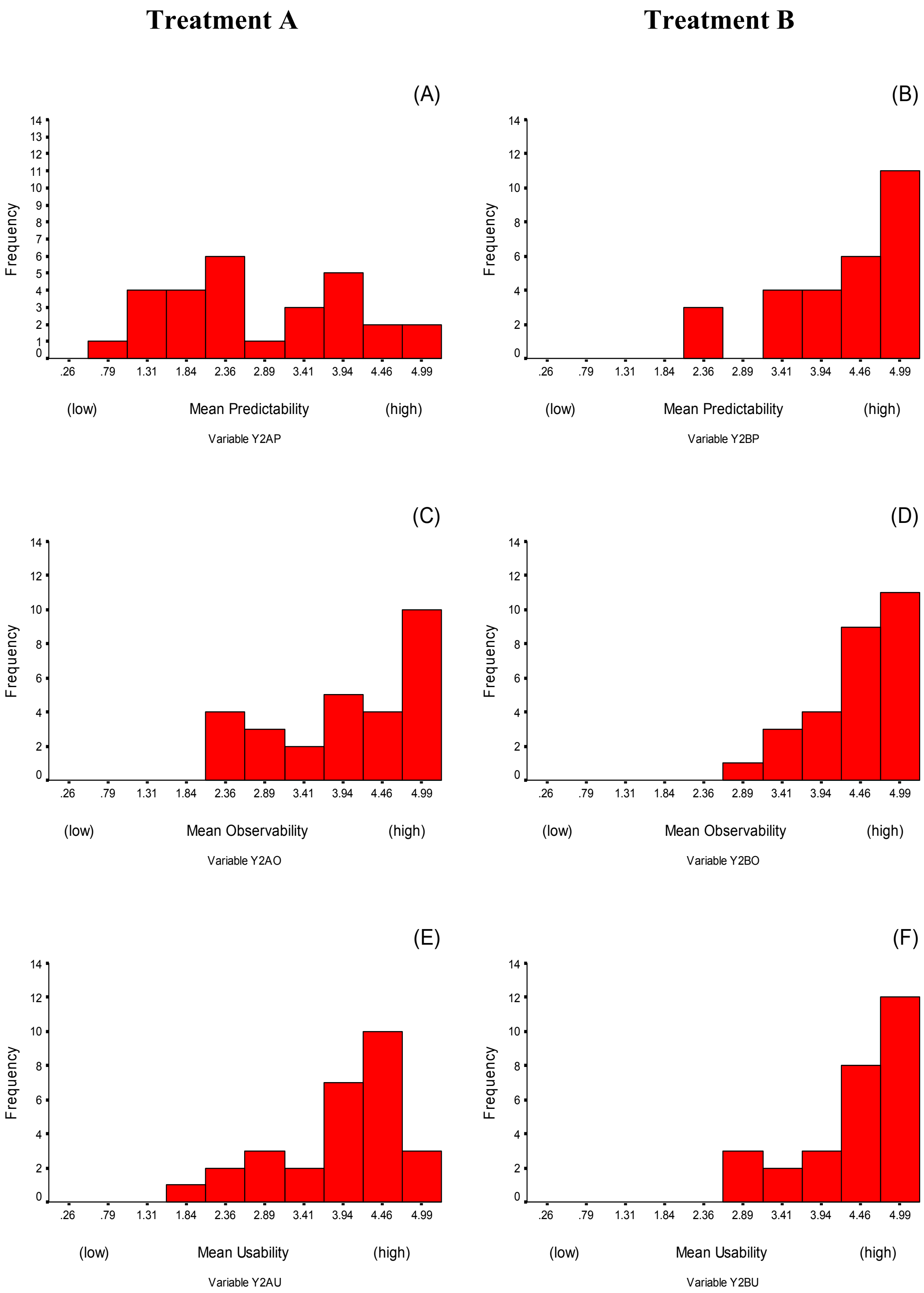

Figure 8-4. The mean predictability, observability, and usability responses for the lighting options scenario. Graphs (A), (E), and (D) depict treatment A responses; graphs (C), (B), and (F) depict treatment B responses. N = 28 subjects.

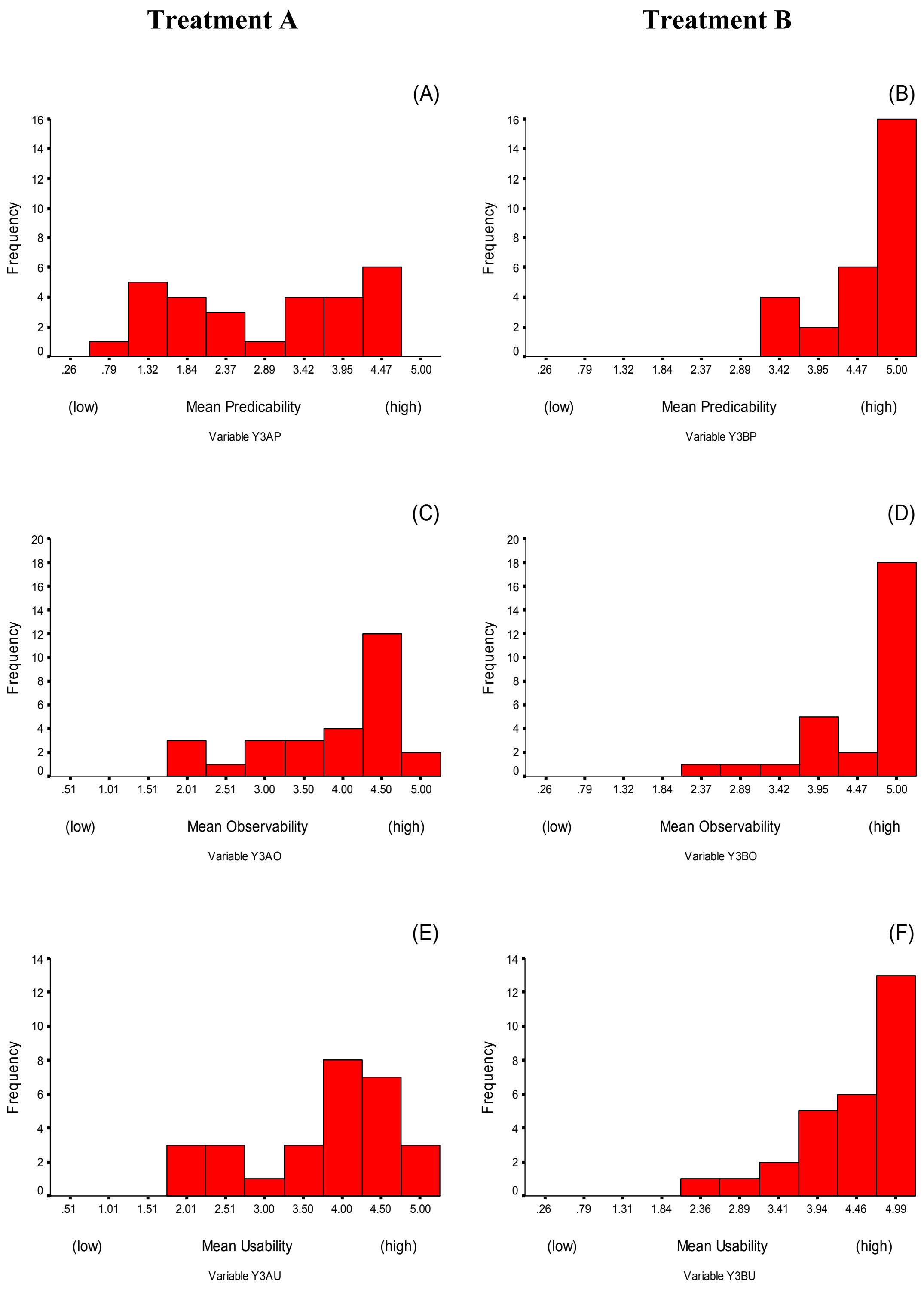

Figure 8-5. The mean predictability, observability, and usability for the wall and window light pushbutton scenario. Graphs (A), (E), and (D) depict treatment A responses; graphs (C), (B), and (F) depict treatment B responses. N = 28 subjects.

In general, the treatment B histograms for predictability, observability, and usability are skewed to the right more than the histograms for treatment A. This indicates treatment B was perceived as having better predictability, observability, and usability than treatment A.

Table 8-1 lists the median and mode subject responses for predictability, observability, and usability for treatment A and B. Observations of these values leads us to infer treatment B was more predictable, observable, and usable because the median and mode values for treatment B all greater than treatment A with only one exception; the mode values are equal for observablility of the lighting option treatments.

Table 8-1. Mean and mode of each dependent variable.

	Vacant light scene treatments		Lighting options treatments		Wall and window light pushbutton treatments	
	A	B	A	B	A	B
Predictability median	2.42	4.38	2.5	4.67	2.64	4.95
Predictability mode	3.0	5.0	2.5	5.0	4.67	5.0
Observability median	3.79	4.38	3.99	4.6	4.14	5.0
Observability mode	3.86	4.0	5.0	5.0	4.71	5.0
Usability median	3.75	4.67	4.0	4.5	4.04	4.25
Usability mode	4.25	5.0	4.0	5.0	4.5	5.0

Analysis of Internal Validity Threats

All subjects answered all questions of the questionnaire (Appendix D) each time they completed a scenario The questionnaire data was checked for internal validity to identify invalid data, to assess data reliability, and to evaluate learning effects and subject fatigue effects.

Outlier Data

Data from two subjects receiving treatment A and two subjects receiving treatment B were determined to be outliers by using three criteria. First, subject data sets having unusually high values were identified. Next, those data sets were compared to the observer's data to identify major discrepancies. For instance, observer data indicated subject frustration and confusion; however, the subject data indicated the opposite.

Data Reliability

Cronbach's Alpha is widely used to estimate data reliability when data are items in a scale; our data is of a five-point Likert scale. The calculated Cronbach's alpha is a reliability coefficient estimate of the data consistency or repeatability given the scale. Chronbach's Alpha values range from 0 to 1; a value of .70 or higher is a typical acceptability benchmark. This was exceeded with Cronbach's Alpha value of .811.

Data Confounding

The subject responses for each dependent variable and treatment are generalized and depicted by line graphs of Figures 8-6 and 8-7. These graphs allow inspection of data trends with respect to the time progression for each scenario as ordered by treatments A and B. The data, as presented in this form, are useful for determining if there might be any confounding from learning effects and subject fatigue. A positive-sloped trend could be an indication that subjects are learning more as time progresses so, they would rate dependent variables with a higher value. A negative-sloped trend could be an indication of subject fatiguing as time increases, so they would rate dependent variables with a lower value. The interpretations of these graphs are given in chapter 9.

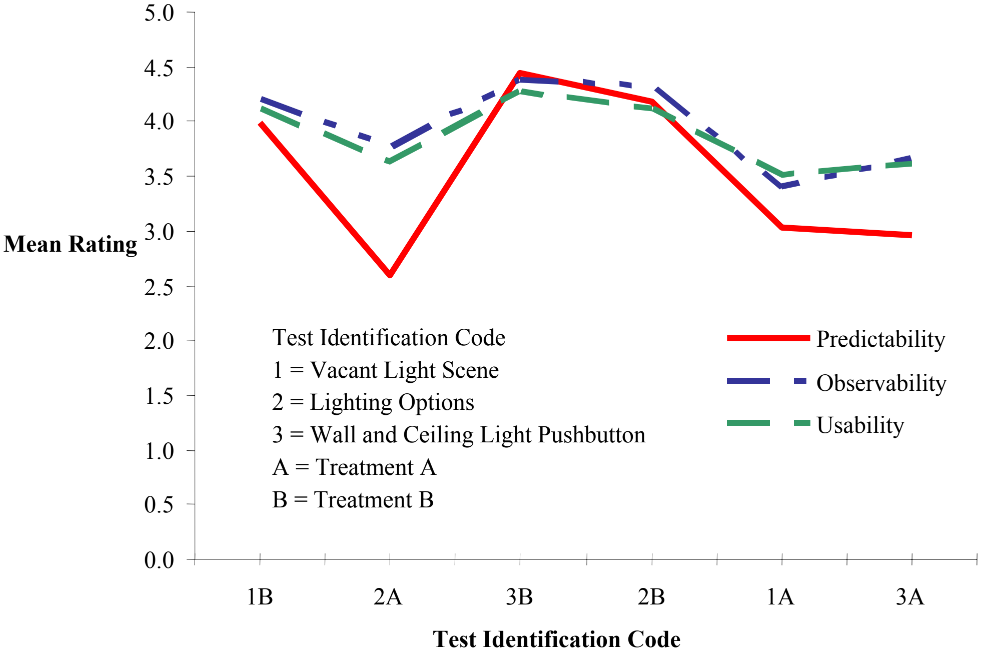

Figure 8-6. The mean dependent variables values for the sequence 1. N = 14.

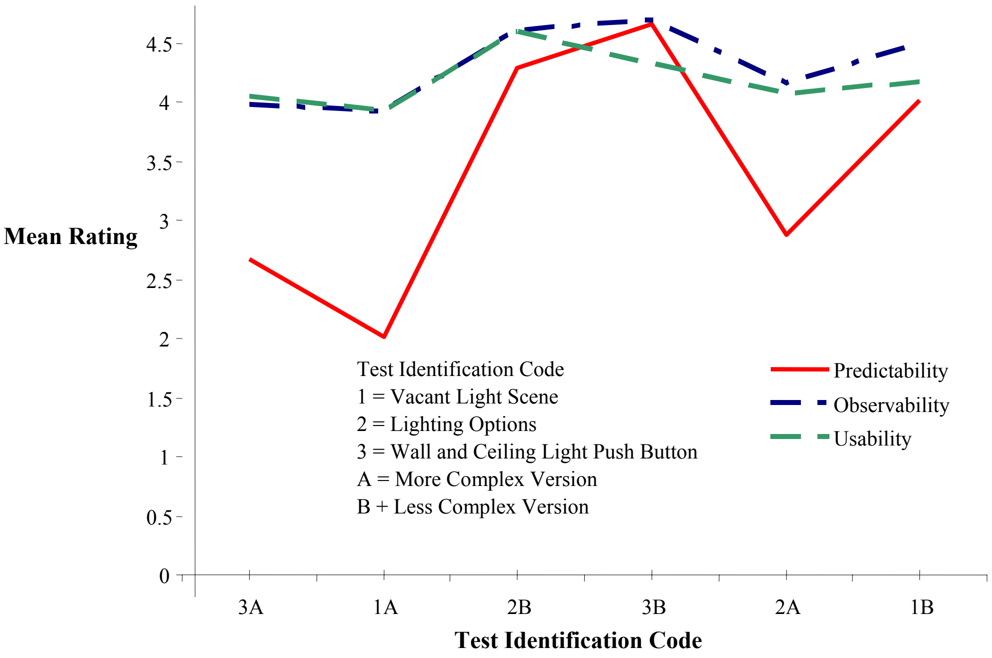

Figure 8-7. The mean dependent variable values for the sequence 2. N = 14.

Hypothesis Testing

Hypotheses 1 through 3 testing used canonical correlation analysis (CCA) was and structure correlations were used to determine linear relationships between the independent and dependent variables. Hypotheses 4 through 6 testing used a one-tailed Wilcoxon signed ranks test to determine the sign and magnitude of differences between treatments A and B. Statistical significance measures for hypotheses tests 1 through 3 was determined by using estimates, via boot-strap re-sampling, of the 95% confidence interval and standard errors. The statistical significance measure for hypotheses tests four through six was determined by using 1-tailed p-values.

Table 8-2 summarizes the hypotheses and the associated statistical methods and statistical significance measures. Subsequent sections detail the inferential statistics.

Table 8-2. Summary of hypotheses and the associated statistical tests.

Hypothesis & Objective	Statistical method and technique	Statistical significance measures	Comments
Hypotheses 1 to 3 Explore relationships between the independent and dependent variables	Canonical correlation analysis (CCA) and structure correlations	Standard error 95% confidence level	- Distribution unknown - Multiple independent variables - Small sample size - Same subjects - Interval & ratio-scaled data
Hypotheses 4 to 6 Test the hypotheses by comparing the directional difference between dependent variables of LCS treatment A (more complex) and treatment B (less complex).	Wilcoxon signed ranks test (one-tailed)	$\alpha = .05$	- Distribution unknown - Small sample size - Related groups - Same subjects - Interval-scaled data

Canonical Correlation Analysis

Canonical correlation analysis (CCA) is one of many multivariate analysis techniques. Other multivariate techniques include multiple regression analyses, multivariate analysis of variance (MANOVA), principle component analysis (PCA), and factor analysis. Each technique has a specific purpose, strengths, weaknesses, and a set of underlying assumptions concerning the type and distribution of data.

CCA was selected for this research because the variables are distinctively and logically grouped as independent and dependent variables as described in chapter 5. CCA is used to identify *multiple* correlations between sets of the independent and dependent variables. This is in contrast to using PCA for analyzing a single data set that does not differentiate between independent and dependent variables. PCA has been effectively used in prior complexity metrics research. Munsen used PCA to explore 35 complexity metrics and concluded it is realistic to believe that software complexity can be characterized with just a few variables (Munsen & Khoshgoftaar, 1989). Ammar (Ammar, Nikzadeh, & Dugan, 1997) also successfully employed PCA for software complexity metrics.

CCA produces a set of paired canonical variates (a variate is a linear combination of variables) representing the sets of independent and dependent variables where the linear combinations are chosen to maximize the correlation. The independent canonical variate consists of a weighted set of the original independent variable set. The weightings of the set's elements are called canonical coefficients. The values of canonical coefficients determine each element's contribution to the independent canonical variate. Likewise, the dependent canonical variable consists of a linear combination of dependent variables.

CCA finds the maximum correlation between the independent and dependent canonical variates and designates this as the first canonical correlation. This first correlation explains the most of the relationship correlation between the independent and dependent canonical variates. The subsequent canonical correlations are ordered in decreasing values of correlation. They are orthogonal to the first set and have a different interpretation. The number of canonical correlations is equal to the number of variables of the smaller set. In this research, the dependent variable set contains three elements; so, only three canonical correlations are estimated.

In summary, the canonical correlation results in two canonical variates, which are linear combinations of elements from the original sets of variables such that a maximum correlation exists between the two canonical variates. Although the result is useful, it is desirable to look at structure correlation coefficients that are the Pearson correlation coefficients between the canonical variates and the original variables.

Canonical Correlation Analysis Process

The canonical correlation analysis involved multiple analyses steps to complete tests of hypotheses 1 through 3. The process steps are summarized:

1. Dependent variable correlation analysis
2. Initial correlation analysis to identify highly correlated independent variables;
3. Canonical correlation analysis to determine structure correlations;
4. Bootstrap resample the data to obtain the standard error and to estimate the 95% confidence interval

Step 1: Dependent variable correlation analysis

A Spearman rank-order correlation analysis was conducted on the dependent variables. The Spearman rank-order correlation is a non-parametric test of the strength and significance of bivariate correlations. Both variables may be ordinal scale. The spearman method calculates a coefficient rho (r_s) as,

$$r_s = 1 - \frac{6\sum d^2}{N^3 - N} \qquad \textbf{(8-1)}$$

where N is the number of observations and d is the difference between each pair of variable rankings. A perfect positive correlation results in $r_s = 1$ while a perfect negative correlation results in $r_s = -1$.

The significance level for the Spearman rank-order correlation coefficient statistics is α = .05. The p-value is used as the test statistic.

Dependent variable correlation analysis results

Table 8-3 depicts the correlation matrix of dependent variables. The results show a medium to high levels of association between the dependent variables. All correlations were significant at < .001 level (1-tailed).

Table 8-3. A matrix of Spearman rank-order correlation coefficient statistics to measure the associations between the dependent variables.

		Predictability	Observability	Usability
Predictability	Correlation coefficient r_s p-value N	1.000 - 168	.638 .000 *** 168	.549 .000 *** 168
Observability	Correlation coefficient r_s p-value N	.638 .000 *** 168	1.000 - 168	.792 .000 *** 168
Usability	Correlation coefficient r_s p-value N	.549 .000*** 168	.792 .000 *** 168	1.000 - 168

*** Correlation is significant at the .001 level (1-tailed)

Step 2: Initial correlation analysis

The original set of independent variables consisted of 15 metrics and are listed in Appendix G. The purpose of step 2 was to first filter out redundancies in this data set. This initial step involved conducting canonical correlation analysis for one independent variable at a time to the set of dependent variables. The results are listed in Table 8-4.

The five highest correlations are in bold. This set of independent variables {*X13, X7, X5, X2, X6*} was used in step 3 that determined the structure correlation coefficients.

Table 8-4. Independent variable correlations to a vector of the three dependent variables. The independent variables with the five highest correlations are in bold.

Independent Variable	Description	Correlation
X13	**Critical-vertex input cyclomatic complexity**	**0.354**
X7	**Critical-state out-degree**	**0.209**
X5	**Critical-state changes**	**0.208**
X2	**Output cyclomatic complexity**	**0.195**
X6	**Critical-state in-degree**	**0.181**
X4	Graph degree	0.139
X14	Critical-vertex output cyclomatic complexity	0.137
X8	Critical-state cyclomatic complexity	0.132
X3	All paths	0.120
X15	Critical-vertex unique conditions	0.116
X9	Critical-state Sheppard complexity	0.180
X12	Critical-vertex Sheppard complexity	0.101
X10	Critical-vertex in-degree	0.092
X11	Critical-vertex out-degree	0.090
X1	Cyclomatic complexity	0.754

Step 3: Structure Correlation

The raw canonical coefficients can be difficult to interpret. Structure correlations are very useful to facilitate their interpretations (Cliff, 1987; Shafto, Degani, & Kirlik, 2003; Degani, 1996). Structure correlations are derived from the raw canonical coefficients and represent the Pearson correlation of each original variable to the canonical variate.

The structure correlations for the first pair of canonical variates are graphically depicted by Figure 8-8 to emphasis the negative correlation between the dependent and independent variates. Table 8-5 lists the structure correlation values. These were the final results.

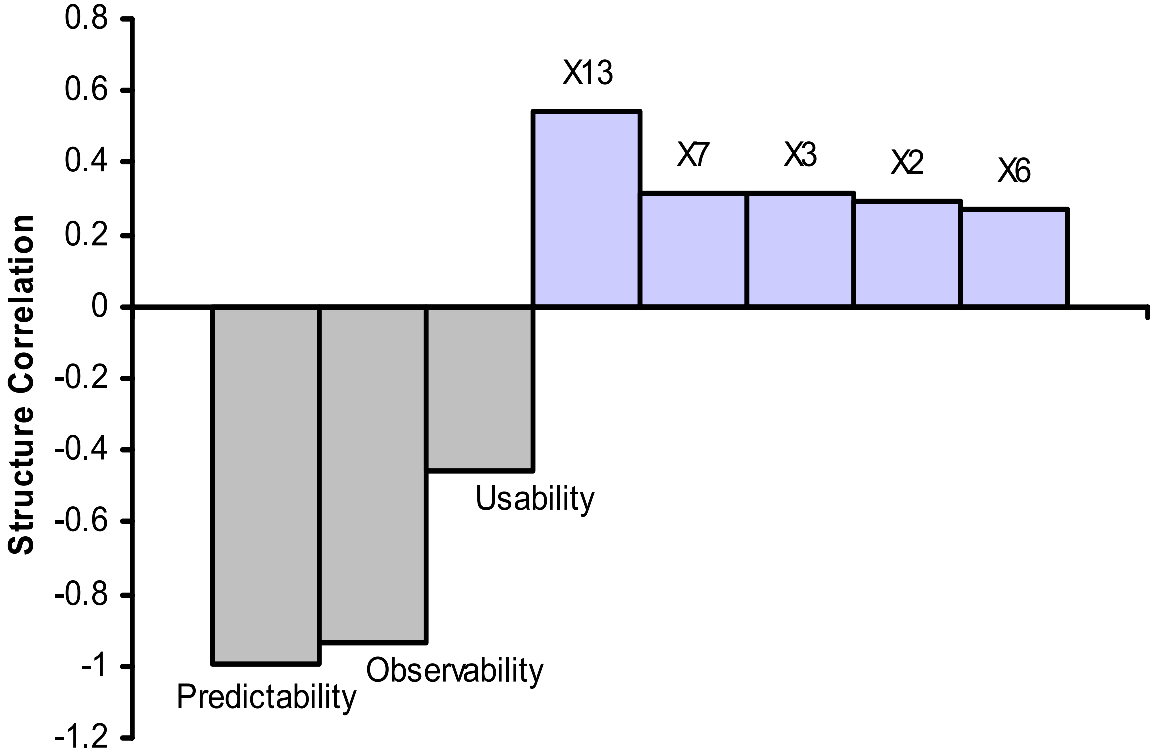

Figure 8-8. A graphical depiction of structure correlations for the first pair of canonical variates. Note the negative correlation between the canonical variates

Table 8-5. Structure correlation values for the first pair of canonical variates.

			Structure correlation
Dependent	Independent	Variables	
√		Predictability (*p*)	-0.993
√		Observability (*o*)	-0.585
√		Usability (*u*)	-0.455
	√	*X13*	0.542
	√	*X7*	0.316
	√	*X3*	0.315
	√	*X2*	0.294
	√	*X6*	0.272

Step 4: Bootstrap Re-sampling

The bootstrap re-sampling method (Efron & Tibshirani, 1993) was used to obtain the estimates of standard error estimate and the 95% confidence limit for the structure correlations. The reason for using bootstrap is that we have no formula for the standard error of a complicated statistic such as the structure correlation.

This method re-samples the data with replacement repeatedly to compute estimates of the desired statistic (structure correlation). In other words, the bootstrap method takes repeated samples to approximate the distribution of the original population. The re-sampling was done preserving the treatment group sample sizes. Thus the re-sampling was stratified by treatment A and B to ensure that each bootstrap sample had 14 observations for treatment A and B (28 total observations)

The results of 1,000 bootstrap samples are listed in Tables 8-6 and 8-7. The mean values listed in Table 8-6 were used as a diagnostic tool to check problems with re-sampling. The mean values from re-sampling are very close to the observed values, thus suggesting the re-sampling was acceptable.

Table 8-6. Statistics from 1,000 bootstrap re-samples of the structure correlations.

Variable	Observed value	Mean value	Standard error
Predictability (*p*)	-0.9925	-0.9854	0.01293
Observability (*o*)	-0.5848	-0.5830	0.08435
Usability (*u*)	-0.4552	-0.4551	0.09648
X13	0.5417	0.5361	0.07596
X7	0.3159	0.3129	0.08953
X5	0.3153	0.3097	0.08834
X2	0.2936	0.2917	0.08835
X6	0.2722	0.2696	0.09122

Table 8-7. Structured correlation confidence limits statistics from 1,000 bootstrap replications of the structure correlations.

Variable	5%	95%
Predictability (*p*)	-0.999	-0.976
Observability (*o*)	-0.712	-0.433
Usability (*u*)	-0.597	-0.280
X13	0.420	0.665
X7	0.175	0.463
X5	0.174	0.461
X2	0.148	0.438
X6	0.127	0.421

Wilcoxon Signed Rank Test

The Wilcoxon signed-rank test (Hollander & Wolfe , 1973) is a nonparametric statistical significance test of the equality of central tendency (median) for two related samples of interval scale. It is used to test the direction and magnitude of difference between a related pair of samples. The Wilcoxon signed rank is calculated as follows, assuming no ties in the data groups:

$$T = \left[R_2 - \frac{n(n+1)}{2} - \frac{1}{2} \right] \div \sqrt{\left(\frac{n(n+1)(2n+1)}{24} \right)} \tag{8-2}$$

where

T = test statistic;

R_2 = ranked sum of negative data group differences;

n = number of nonzero data group differences;

If there are ties in the data groups, the Wilcoxon signed rank test is calculated as follows:

$$T = \left[R_2 - \frac{n(n+1)}{2} - \frac{1}{2} \right] \div \sqrt{\left(\frac{n(n+1)(2n+1)}{24} - \sum_{i=1}^{g} \frac{t_i^3 - t_i}{2} \right)} \tag{8-3}$$

where

t_i = number of differences of equal absolute values in the i^{th} tied group;

g = number of tied data groups;

If T > $Z_{1-\alpha/2}$ then reject H_o, else accept H_o. The p-value is calculated by

$$\rho = 2 \text{ x } [1-\Phi(T)] \tag{8-4}$$

Z is a standard normal (Gaussian) random variate (with mean 0 and variance 1) and Phi is the standard normal cumulative distribution function.

The related pair of samples has a significant difference if the calculated value of T is equal or less than the critical Wilcoxon's T value. The software program SPSS, used in this research, calculates a *Z*-test statistic for the Wilcoxon signed rank test. The critical value of *Z* is ±1.645 for a significance level of .05.

The Wilcoxon signed-rank test is used to test hypothesis 4 through 6. The dependent variable data for predictability, observability, and usability from all scenarios using treatment A was compared to dependent variable data for predictability, observability, and usability from all scenarios using treatment B, the less complex version of treatment. Table 8-8 lists the results.

Table 8-8. Wilcoxon signed ranks test results of all scenarios.

Wilcoxon Signed Ranks Test (1-tailed)	Predictability Treatments B - A	Observability Treatments B - A	Usability Treatments B - A
Z	-7.230[a]	-6.014[a]	-5.574[a]
p-value	.000***	.000 ***	.000 ***

a. Based on negative ranks
*** Correlation is significant at the .001 level (1-tailed).

A more detailed analysis was conducted to strengthen the validity of hypothesis 4 through 6 test results. Wilcoxon signed ranks test were conducted to test hypothesis 4 through 6 for each scenario. The results, listed by Table 8-8, showed that subjects perceived the test scenario outcomes on the complex system (treatment A) as less predictable, observable, usable in comparison to the simpler system (treatment B).

Table 8-9. Wilcoxon signed ranks test results for each scenario.

Scenario	Wilcoxon Signed Ranks Test. (1-tailed)	Predictability Treatments B - A	Observability Treatments B - A	Usability Treatments B - A
1) Vacant light scene	*Z* p-value	-4.339[a] .000 ***	-3.581[a] .000 ***	-3.140 [a] .001
2) Lighting 0ptions	*Z* p-value	-4.073[a] .000 ***	-2.987[a] .002	-3.019[a] .002
3) Wall and window light pushbuttons	*Z* p-value	-4.373[a] .000 ***	-4.017[a] .000 ***	-3.194[a] .000 ***

a. Based on negative ranks.
*** Correlation is significant at the .001 level (1-tailed).

Summary

Descriptive statistics were presented to describe the subject characteristics data and subject response data for warm-up tests and the scenario tests. Next, an internal validity threat analysis was conducted to target invalid data, data reliability, and data confounding from learning effect and subject fatigue. The results do not show significant internal validity threats from these sources. Hypotheses testing commenced once data validity was verified.

Canonical correlation analysis and structure correlations were used to test hypotheses 1 through 3 − the dependent variables predictability, observability, and usability correlate with our NAT metrics of complexity. The results showed structure correlations exceeding .25 for five metrics, standard errors of less than .10, and a statistically significant 95% confidence interval. The five NAT metrics that correlated with our dependent variables were: *X15,* the critical-vertex input cyclomatic complexity; *X7,* the critical-state out-degree; *X5,* the number of critical state changes; *X2,* the output cyclomatic complexity; *X6*, the critical state in-degree. A Wilcoxon signed ranks test was used to test hypotheses 4 through 6 and the results were also statistically significant. The results showed that subjects perceived the test scenario outcomes of the complex system (treatment A) as less predictable, observable, usable in comparison to the simpler system (treatment B).

Literature Cited

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CHAPTER 9
DISCUSSION

This chapter addresses two core questions of this research: Does the data support the research hypotheses and, what is the meaning and significance of the results.

The acceptance or rejection of each research hypotheses is based on inferences from two parts: 1) the analysis and interpretation of internal validity threats common to all hypotheses; 2) the statistical test criteria for acceptance. Following this is a discussion of the implications, limitations, and future areas of research.

Relevant Data for all Hypotheses

The acceptance or rejection of a research hypothesis based solely on statistical test criteria results in a weakly supported inference. Potentially, numerous threats to internal validity can exist so, type I or II errors could result. This section discusses the steps taken to reduce internal validity threats.

Internal Validity Threats

Each potential threat is listed and discussed as follows:

- *Data confounding from the scenario instructions:* Subject responses for the dependent variables predictability, observability, and usability could be biased due to subjects having difficulty following and understanding scenario instructions.

  This seems unlikely based on the warm-up data for variable W1− the mean value for the subject's ease of following and understanding the warm-up instructions. Of 28 subjects, 24 rated W1 very favorably with a greater than 3.94 out of a maximum of 5.0. The distribution for W1 had a positive skew to the right (the highest score) as depicted by Figure 9-1(A).

- *Data confounding from the GUI:* Biased responses for the dependent variables predictability, observability, and usability could be due to subjects having difficulty with the GUI.

This seems unlikely based on the warm-up data for variable W2− the mean value for the subject's ease of using the GUI to run the warm-up. Of 28 subjects, 24 rated W2 greater than 3.58 out of a maximum of 5.0 score. The distribution forW2 had a positive skew to the right (the highest score) as depicted by Figure 9-1(B).

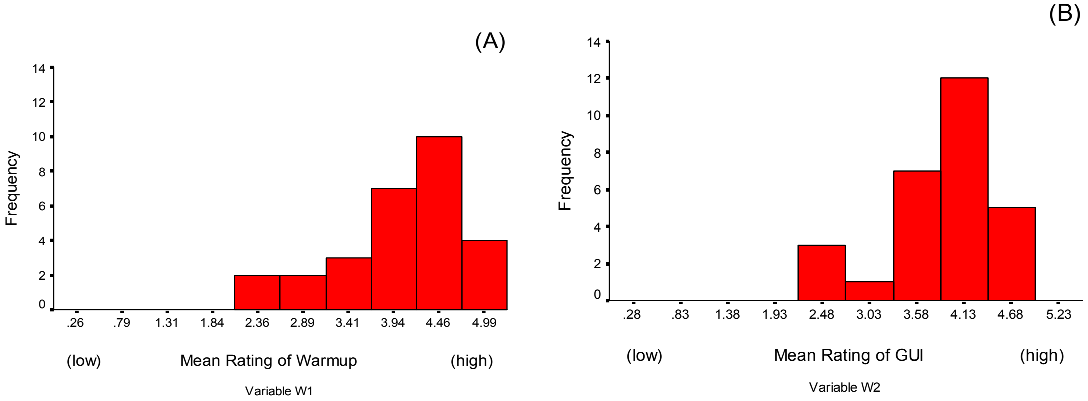

Figure 9-1. Mean subject responses for the warm-up session. Graph (A) depicts the ease following and understanding the warm-up instructions. Graph (B) depicts the GUIs ease of use.

- *Invalid data:* Data from four subjects was eliminated because of consistent strings of high ratings and because this data was inconsistent with observer's data. For instance, out of 36 questions, 34 were rated 5.0 and two questions near the end of the questionnaire were rated 4.0.

- *Data reliability:* The data reliability was accepted given Cronbach's Alpha = .811. An alpha of .70 or higher is a typical benchmark of acceptability.

- *Learning effects or subject fatigue:* From inspection of data trends, one can infer learning effects and fatigue. A positive-sloped trend could be an indication that subjects are learning more as time progresses so, they would rate dependent variables with a higher value. A negative-sloped trend could be an indication of subject fatiguing as time increases, so they would rate dependent variables with a lower value. The data trends of Figures 9-2 and 9-3 were used to infer data confounding from learning effects or fatigue for treatments A or B. We failed to detect trends indicating data confounding.

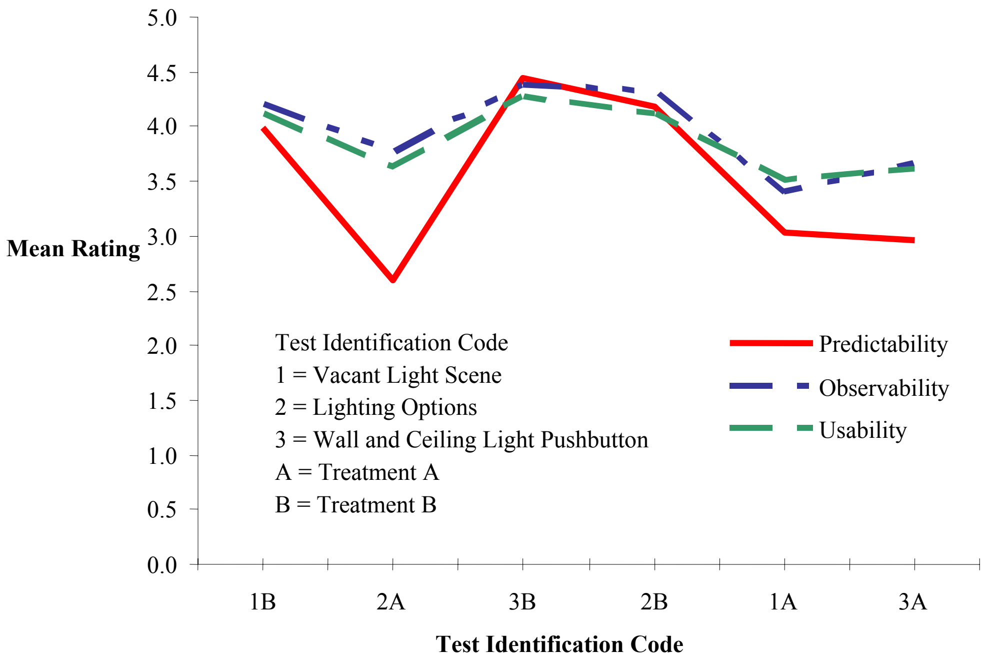

Figure 9-2. The mean values of each dependent variable for the sequence 1 test order. N = 14 subjects

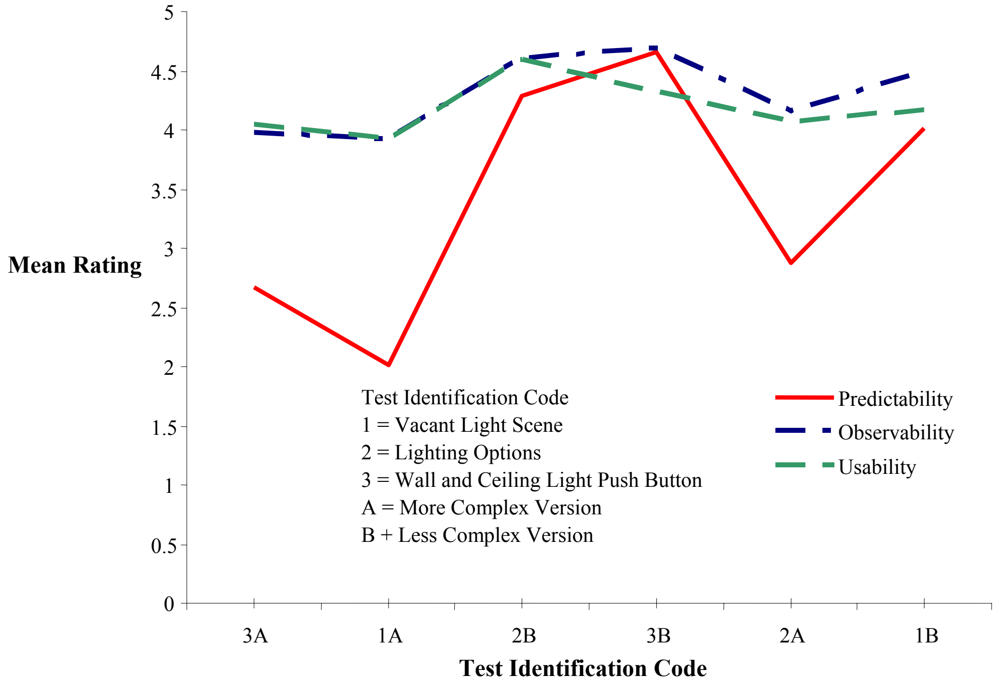

Figure 9-3. The mean values of each dependent variable for the sequence 2 test order. N = 14 subjects.

Hypotheses 1 Through 3

The first three research hypothesis concern the existence of correlations between subject perceptions of the system (the dependent variables of predictability, observability, and usability) and NAT metrics of system complexity (the independent variables). Fifteen NAT metrics of system complexity comprised the set of independent variables.

The hypotheses are summarized as follows:

Hypothesis 1:

H_0: There is not a correlation between NAT metrics and system predictability.

H_1: NAT metrics are correlated to system predictability.

Hypothesis 2:

H_0: There is not a correlation between NAT metrics and system observability.

H_1: NAT metrics are correlated to system observability.

Hypothesis 3:

H_0: There is not a correlation between NAT metrics and system usability.

H_1: NAT metrics are correlated to system usability.

Relevant Data

Five out of 15 metrics had a statistically significant structure correlation to the set of dependent variables as depicted by Table 9-1. The statistical significance was established from 1,000 bootstrap re-sampling calculations (as previously described in section "Step 4: Bootstrap Re-sampling" of chapter 8.) for standard error and a 95% confidence interval.

Table 9-1. Structure correlations and statistical significance measures for the first pair of canonical variates.

Independent variables	Structure correlation	Standard error	Confidence limits 5%	95%
X13	0.542	0.07596	0.420	0.665
X7	0.316	0.08953	0.175	0.463
X5	0.315	0.08834	0.174	0.461
X2	0.294	0.08835	0.148	0.438
X6	0.272	0.09122	0.127	0.421

Generally, structure correlations less than .30 are dropped because the contribution to the canonical variate is minimal (Shafto, Degani, & Kirlik, 2003); This benchmark was relaxed to .25; hence, the entire set of independent variables {*X13, X7, X5, X2, X6*} were included for the first canonical variate. The benchmark was relaxed because this portion of the research is largely exploratory, and because the information content of the independent data was limited. as compared to the dependent variable data. The independent variable data contained only 16 unique values; the dependent variable data has 168 unique values.

Next, the standard error and confidence interval are calculated for each structure correlation. A standard error less than .100 is acceptable for exploratory research; all the standard errors listed in Table 9-1 meet these acceptance criteria. The 95% confidence limit is exampled as follows:

> A confidence interval gives an estimated range of values which is likely to include an unknown population parameter, the estimated range being calculated from a given set of sample data.
>
> If independent samples are taken repeatedly from the same population, and a confidence interval calculated for each sample, then a certain percentage (confidence level) of the intervals will include the unknown population parameter. Confidence intervals are usually calculated so that this percentage is 95% …
>
> Confidence limits are the lower and upper boundaries / values of a confidence interval, that is, the values which define the range of a confidence interval. The

upper and lower bounds of a 95% confidence interval are the 95% confidence limits (Easton & McColl, 2003).

None of the confidence intervals in Table 9-1 include zero; therefore, the estimates of structure correlations confidence levels are statistically significantly different from zero (alpha = 0.05).

Null Hypotheses Rejection

The null hypothesis was rejected hypothesis 1, 2, and 3. This was based on hypotheses test results of structure correlations exceeding .25 as shown by Table 9-1, standard errors of less than .10, confidence intervals that are statistically significant as shown by Table 9-2, and the steps to reduce internal validity threats.

Hypotheses 4 Through 6

The last three research hypothesis concern the existence of decreasing directional differences between subject perceptions of LCS treatment A (more complex) and LCS treatment B (less complex). The hypotheses are summarized as follows:

Hypothesis 4:

H_0: Increasing interactive complexity does not decrease system predictability.

H_1: Increasing interactive complexity decreases system predictability.

Hypothesis 5:

H_0: Increasing interactive complexity does not decrease system observability.

H_1: Increasing interactive complexity decreases system observability.

Hypothesis 6:

H_0: Increasing interactive complexity does not decrease system usability.

$H_{1:}$ Increasing interactive complexity decreases system usability.

Relevant Data

The resulting Wilcoxon signed-ranks test results listed by Table 9-2 show highly negative differences between the dependent variables of treatments A and B. This means the median of the population distribution from treatment A was less than the median of the population distribution from treatment A; simply, treatment A was more complex than treatment B. Secondly, the differences between treatment medians are very highly statistically significant with p-values less than 0.001 (one-tailed). P-values are explained as follows:

> The probability value (p-value) of a statistical hypothesis test is the probability of getting a value of the test statistic as extreme as or more extreme than that observed by chance alone, if the null hypothesis H_0, is true.
>
> It is the probability of wrongly rejecting the null hypothesis if it is in fact true.
>
> It is equal to the significance level of the test for which we would only just reject the null hypothesis. The p-value is compared with the actual significance level of our test and, if it is smaller, the result is significant. That is, if the null hypothesis were to be rejected at the 5% significance level, this would be reported as "p < 0.05".
>
> Small p-values suggest that the null hypothesis is unlikely to be true. The smaller it is, the more convincing is the rejection of the null hypothesis. It indicates the strength of evidence for say, rejecting the null hypothesis H_0, rather than simply concluding "Reject H_0' or "Do not reject H_0" (Easton & McColl, 2003).

Table 9-2. Wilcoxon signed-ranks test results an aggregation of all scenarios.

Wilcoxon Signed-ranks test (1-tailed)	Predictability Treatments B - A	Observability Treatments B - A	Usability Treatments B - A
Z	-7.230[a]	-6.014[a]	-5.574[a]
p value	.000***	.000 ***	.000 ***

b. Based on negative ranks
*** Statistical significance < .001 (one-tailed)

The results depicted by Table 9-2 indicate that treatments are different with regard to predictability, observability and usability, and the directional differences indicate that treatment A has the larger median values. Wilcoxon signed-ranks test were conducted to test hypothesis 4 through 6 for each scenario. The results are listed by Table 9-3.

Table 9-3. Wilcoxon signed-ranks test results for each scenario.

Scenario	Wilcoxon Signed-ranks test (1-tailed)	Predictability Treatments B - A	Observability Treatments B - A	Usability Treatments B - A
1) Vacant light scene	*Z* p value	-4.339[a] .000 ***	-3.581[a] .000 ***	-3.140 [a] .001**
2) Lighting 0ptions	*Z* p value	-4.073[a] .000 ***	-2.987[a] .002**	-3.019[a] .002**
3) Wall and window light pushbuttons	*Z* p value	-4.373[a] .000 ***	-4.017[a] .000 ***	-3.194[a] .000 ***

a. Based on negative ranks.
** Statistical significance ≤ .01 (one-tailed)
*** Statistical significance ≤ .001 (one-tailed)

The results showed a significant directional difference and that treatment A has the larger median value for each scenario. These are very highly significant statistical differences with p values less than < .001 (one-tailed) except for observability and usability for the Lighting options scenario that has a highly significant statistical difference with a one-tailed p-value of 0.002. The results of this in-depth analysis also support rejection of the null hypotheses.

Lastly, the hypotheses testing results for research hypotheses 1 through 3 give added insight. Specifically, the graphical depiction of structure correlations for the first pair of canonical variates, depicted by Figure 9-4, shows very strong negative structure correlations for the canonical variate composed of the original dependent variables (note that a perfect negative correlation is -1); therefore, as the independent variables *X13*, *X7*, *X5*, *X2*, and *X6* increase, the dependent variables of predictability, observability, and usability decrease.

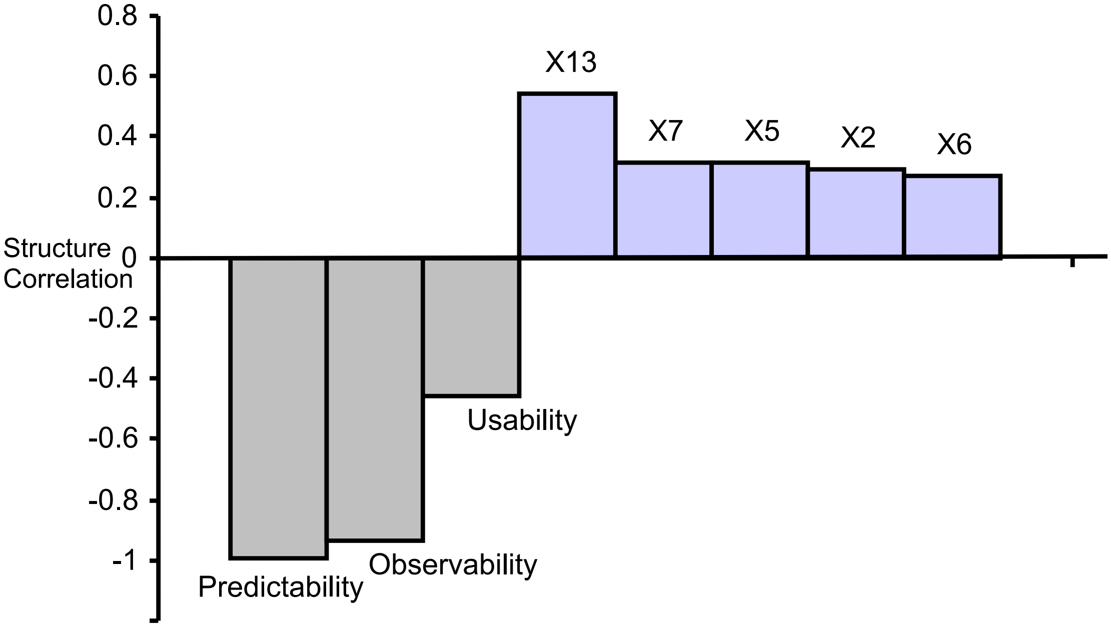

Figure 9-4. A graphical depiction of structure correlations for the first pair of canonical variates. Note the negative correlation between the canonical variates.

Null Hypotheses Rejection

The null hypotheses are rejected for research hypothesis 4, 5, and 6. The rejection was based on the Wilcoxon hypotheses test results of Tables 9-2 and 9-3 showing that treatment A was perceived by subjects as more complex than treatment B; also, the p-values of these results exceeded the statistical significance level of 05. Secondly, the strong negative correlations between independent and dependent structure correlations, depicted by Figure 9-4, supported the decision to not accept the null hypotheses.

Implications

This research can be used as a practical tool for addressing system-level hazards in embedded-computer based systems. Specifically, the hazards are those resulting from NAT complexities. Mitigation of these hazards is very important because computer-based systems are proliferating in many safety-critical applications and many incidents have occurred. Over 400 computer-related incidents have been documented (Neumann, 1995). In 1995, about 2000 deaths were determined to be computer-related (MacKenzie, 1994). In the mining sector, 82 computer-related incidents from 1995 to 2001 were documented (Sammarco, 2003). The mining incidents involved the hazard of unexpected movement. This is a significant hazard so NIOSH research is addressing this by developing best practice recommendations and the NAT complexity assessment methodology of this research (Sammarco, 1999). The existence of this safety issue is troubling, but more troubling is that our traditional tools do not effectively handle complexity-related hazards (Leveson, 2000).

This research enables quantification of NAT complexities of system-level requirements. This enables NAT complexities impacting safety to be identified, analyzed, and mitigated before they are propagated to subsequent life cycle phases. Safety is an emergent property of the system so safety must be addressed at the system-level as done by this research. This is in contrast to other approaches that quantify attributes of the software subsystem. Obviously, these approaches do not address the system but they also take place much later in the system life cycle where the software is already written. Thus, it is more costly to correct.

The implications of this research are discussed in detail through means of a practical example addressing the important issue of requirements errors.

Requirements Engineering

The vacant light scene scenario, first described in chapter 6, serves to illustrate a practical engineering application involving an incompletely defined function. The practicality and importance of this research is strengthened by this illustration because of the nature of requirements errors; most errors occur in the requirements (Davis, 1993) (Lutz, 1996); errors are much less costly to correct at the requirements phase than later

(Davis, 1993) (Nelson, Clark, & Spurlock, 1999); requirement errors propagate to cause errors in later life cycle phases (Kelly, Sherif, & Hops, 1992).

Requirement specification errors fall into two categories: errors of omission and errors of commission. Requirements errors are common. A study of primary causes of failure for 34 industrial accidents found that 44.1% of the causes were attributed to the requirements specification (UK Health and Safety Executive, 1995). Similar results were found for the mining sector (Sammarco, 2003).

Secondly, it is very beneficial to address requirements issues early in the requirements phase, where most of the errors occur, because it is less costly to correct them compared to later development stages (Davis, 1993; Jones, 1994).

The vacant light scene scenario provides an example of an error of omission because the functionality is incompletely specified. The vacant light scene scenario is now described.

The vacant light scene

The vacant light scene for treatments A and B is summarized by the listings in Table 9-4. The behaviors for treatments A and B are identical up to the time of five minutes. At that time, the vacant light scene activates and remains activated for treatment B (the less complex system). Treatment A differs in that the vacant light scene does not activate until the subject re-enters the office at seven minutes.

The LCS requirement U4 of section 3.1.1 of the LCS problem description, defines the behavior for the vacant light scene (Queins et al., 2000). It states:

> “If the room is reoccupied after more than T1 minutes after the last person has left the room, the *default light scene* has to be established.”

Both treatments meet the LCS requirements for the vacant light scene because for treatments A and B, the vacant light scene is “on” when the subject reoccupies the office after the time delay expired. The requirements defining the vacant light scene operation are incomplete, thus there is an error of omission.

Table 9-4. Vacant light scene scenario values for treatment A and B. The items of primary interest are in bold.

Time (Minutes)	LCS Mode	Light Scene	Treatment A Vacant Light (Window)	Treatment B Vacant Light (Window)
0	occupied	occupied	disabled	disabled
1	temp. empty	occupied	disabled	disabled
2	temp. empty	occupied	disabled	disabled
3	temp. empty	occupied	disabled	disabled
4	temp. empty	occupied	disabled	disabled
5 (delay time)	**temp. empty**	**vacant**	**disabled**	**enabled @ 20 watts**
6	temp. empty	vacant	disabled	enabled @ 20 watts
7	**occupied**	**vacant**	**enabled @ 20 watts**	**enabled @ 20 watts**

The complexity assessment methodology of this research can be used as a tool to help decide which design, treatment A and B, is less complex. In less complex designs the end-user is not likely to create a hazardous situation because the system is less predictable, observable, and useable (the dependent variables of this research).

This research can be used as a tool to help improve system safety early in the requirements phase where interventions are the most cost-effective.

Limitations

Three primary limitations of this research are listed in order of priority and discussed. The last two limitations concerning human subjects and external validity are interrelated.

Predictive limitations:

The complexity assessment methodology of this research involves relative comparisons of systems under development or of existing systems. At this point, it has limited use as a prediction tool or system. A prediction system is defined to clarify this limitation:

> "A prediction system consists of a mathematical model together with a set of prediction procedures for determining unknown parameters and interpreting results." (Littlewood, 1989)

This research is useful for *relative assessments* but it lacks mathematical models and inference procedures to identify and assign a probability to future outcomes. This research does not establish benchmarks for the independent variables *X13*, *X7*, *X5*, *X2*, and *X6*. Thus, at this point, one cannot infer with a great degree of certainty that the value of any independent variable should not exceed a specific benchmark. If the research did establish these benchmarks, then one could use them to target specific areas for simplification. Hence, additional research is needed to realize a predictive tool. The complexity assessment methodology of this research can serve as a solid basis for predictive research.

Limited subject diversity

The data from our volunteer subject characterizations indicates a relatively homogenous group of people. The potential exists that subjects had similar perceptions because of the homogenous makeup of the group. Therefore, this can potentially be a threat to external validity with respect to generalizations to other populations.

Subject data was collected during pre-test activities. Analysis of subject data shows that there were very small numbers of people with non-technical backgrounds, people in the 18 to 35-age range, and women. The most predominate characteristics are as follows:

- 78.1% - technical job classification;
- 71.8% - 45-65 years old;
- 87.3% - male;
- 84.4% - PC experience rated at 4 or 5 (expert).

There is a positive aspect to the sample population limitations. We infer that it was more difficult to elicit negative subject perceptions of system predictability, observability, and usability (the dependent variables) because the typical subject had considerable experience with technical systems and PC's. This was an advantage because their mental models of the system most likely included a more complete structural model of the system because they had researched, designed, and analyzed other complex, technical systems at NIOSH. Some subjects commented they had figured out how the more complex LCS (treatment A) was designed.

The dependent variable measurements are based upon user perceptions. Human perceptions are affected by many factors including age, race, gender, education, and social factors; hence, perceptions can potentially contain a large degree of variability.

The subjects are a limited sample of the population. This can be a threat to external validity; however, the years of technical experience could have given the volunteer subjects an advantage over more generalized sample populations.

External validity

The research is externally valid if it can be generalized to other populations or to other embedded computer systems. The external validity limitations that could affect generalization to other populations were addressed. It is not known if the resulting set of independent variables is useful for other systems, or if the same inferences concerning the six research hypotheses would pertain to other systems.

There is a *potential* lack of generalization to other systems; however, this is not an obvious or intrinsic threat to external validity because this research focuses on a complexity assessment methodology and not the specific results with respect to the specific metrics comprising the set of independent variables. More importantly, the methodology can be generalized to other systems. Specifically, the SCR tools have been successfully used to model a wide variety of complex, real-time embedded systems including avionics systems, a submarine communications system, and safety-critical portions of a nuclear power plant (Heitmyer, Jeffords, & Labaw, 1996). Secondly, the metrics of this research are not specific to a given system but can be determined from any SCR dependency graph.

More research using other subject samples and systems is needed to verify the extent of external validity with respect to the specific results. However, it can be stated that the complexity assessment methodology of this research can be generalized to other systems and subject populations.

Summary

Canonical correlation analysis and structure correlations were used to test null hypotheses 1 through 3 −the dependent variables predictability, observability, and usability do not correlate with our NAT metrics of complexity. The results showed structure correlations exceeding .25 for five metrics, standard errors of less than .10, and a statistically significant 95% confidence interval. The five NAT metrics that correlated with our dependent variables were: *X15*, critical-vertex input cyclomatic complexity; *X7,* critical-state out-degree; *X5,* number of critical state changes; *X2*, output cyclomatic complexity; *X6*, critical state in-degree.

A Wilcoxon signed ranks test was used to test null hypotheses 4 through 6 − increasing NAT complexity does not decreases system predictability, observability, and usability. The results showed that subjects perceived the test scenario outcomes of the complex system (treatment A) as less predictable, observable, usable in comparison to the simpler system (treatment B).

Based on hypotheses test results and the steps to guard internal validity, the null hypotheses were rejected for research hypotheses one through six.

Lastly, the primary limitations of this research concern the research's limited use as a predictive tool and potential threats to validity because continence subjects were used and because this research is just one empirical study. More empirical research is needed to address these limitations.

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CHAPTER 10
SUMMARY AND CONCLUSIONS

Summary of Research

Normal Accident Theory (NAT) explains that complex system accidents are inevitable because complex systems, such as computer-based systems, are highly interconnected, highly interactive, and tightly coupled. For example, over 400 computer-related incidents occurred between 1976 and 1963 (Neumann, 1995). From 1995 to 2001, 11 computer-related mining incidents in the U.S. were reported by the Mine Safety and Health Administration; from 1995 to 2002, 71 computer-related mining incidents were reported in Australia (Sammarco, 2003). The National Institute for Occupational Safety and Health (NIOSH) has recognized the hazards associated with complex computer-based mining systems; hence, it is developing a complexity assessment methodology for programmable-electronic mining systems (Sammarco, 2002).

We are ill-equipped to understand and manage these complexities because we have not had a scientific methodology to identify and quantify the safety-related complexities of a system. More specifically, NAT has not been operationalized for computer-based systems. Our research addresses this limitation. Our specific objective was to define graph-theoretical metrics to measure or indicate specific NAT attributes of complexity in the system requirements of computer-based systems.

We theorized there are two types of system complexity. The first is internal − the complexity of a system's internal structure. The second is external − the unfamiliar, unplanned, or unexpected system behaviors as viewed by the human interacting with the system. External, complex behaviors can be difficult to observe and not immediately comprehensible by the end-user (Perrow, 1999). We characterized external complexity with three variables: predictability, observability, and usability — the dependent variables for our research. We characterized internal complexity by modeling a system's specified behavior, and quantifying its NAT attributes with multiple graph-theoretical metrics — our independent variables.

The first challenge was to formally model the specified behavior (requirements) of a computer-based system such that the model enabled direct or indirect measurement of internal complexity. Twelve criteria were established to help guide the selection of a modeling method. The Software Cost Reduction (SCR) method was selected and successfully used to translate system requirements into dependency graph models to which we could apply our graph-theoretical metrics.

The next challenge was to define multiple, graph-theoretical metrics to measure or indicate specific NAT attributes. This was accomplished by deduction — abstracting the thirteen attributes of NAT complexity, as conceptualized by Perrow (Perrow, 1999), to a generalized view of simple (linear) and complex (nonlinear) systems; selecting a subset of NAT attributes pertaining to system requirements; deriving multiple metrics for the subset of NAT attributes. As a result, fifteen metrics were proposed.

Next, the light control system (LCS) was selected as research test vehicle because it represented a complex, real-world system that afforded human-computer interaction. The LCS was devised by the Fraunhofer Institute for Experimental Software Engineering as a case study for requirements engineering seminars. With the research test vehicle in place, we addressed our research methodology.

The research methodology was based on a cross-over design. We chose a standard design because its validity was established, and the strengths and weaknesses were well known. Our methodology included having 32 volunteer subjects run simulations of the LCS in order for us to obtain dependent variable data. The data were collected from a questionnaire each subjected answered after running a simulation. Once data were collected, we conducted an internal validity threat analysis. Significant internal validity threats were not evident so we prepared the data for hypotheses testing.

Canonical correlation analysis and structure correlations were used to test null hypotheses 1 through 3 − the dependent variables predictability, observability, and usability do not correlate with our NAT metrics of complexity. The results showed structure correlations exceeding .25 for five metrics, standard errors of less than .10, and a statistically significant 95% confidence interval. The five NAT metrics that correlated with our dependent variables were: *X15*, critical-vertex input cyclomatic complexity; *X7,* critical-state out-degree; *X5,* number of critical state changes; *X2*, output cyclomatic complexity; *X6*, critical state in-degree. A Wilcoxon signed ranks test was used to test null hypotheses 4 through 6 − increasing NAT complexity does not decrease system predictability, observability, and usability. The results showed that subjects perceived the test scenario outcomes of the complex system (treatment A) as less predictable, observable, usable in comparison to the simpler system (treatment B). Based on hypotheses test results and the steps to guard internal validity, the null hypotheses were rejected for research hypotheses one through six as summarized by Table 10-1.

Table 10-1. A summary of the research hypotheses and associated rejection criteria

Null Hypothesis H_0	Do not Reject H_0	Reject H_0	Rejection criteria
1) There is not a correlation between NAT metrics and system predictability.		X	Structure correlation ≥ .250 Standard error ≤.100 95% Confidence interval does not cross zero
2) There is not a correlation between NAT metrics and system observability.		X	
3) There is not a correlation between NAT metrics and system usability.		X	
4) Increasing interactive complexity does not decrease system predictability		X	Wilcoxon sign-ranks test $Z \leq -1.645$ p value ≤ .05
5) Increasing interactive complexity does not decrease system observability		X	
6) Increasing interactive complexity does not decrease system usability		X	

We reflect on the implications of this research. Our research quantified NAT complexities of system-level requirements. This enables an early assessment of NAT complexities impacting safety before they are propagated to other life cycle phases. Our research can be used as a requirements engineering tool to compare NAT complexity impacts from various system requirements. Armed with this knowledge, one can target requirements to simplify, and measure their simplification efforts.

In subsequent sections, we draw a number of conclusions about the research; identify the research limitations, and the opportunities for future research.

Conclusions

Several conclusions emerge from this research; these conclusions are based on data and what was observed and learned. We conclude that this work is a promising and significant step in meeting our research objective: to operationalize NAT for the system-level requirements of safety-related computer systems. Several other conclusions are drawn with respect to the four specific aims of the research, and lastly, it was concluded that this research has several limitations and that there are opportunities for future research.

Conclusion 1

The research objective was partially realized. We qualify this claim as partial because the research was limited to one system and 32 test subjects; more empirical research is needed to validate the findings. Nonetheless, we have carried out the first steps to take NAT from theory to practice. Two arguments support this claim. First, there was a statistically significant, negative correlation between five NAT metrics of complexity and the externally visible system attributes of predictability, observability, and usability. Secondly, we realized each of the specific aims for operationalizing NAT with respect to the research objective.

- Specific Aim 1: Identify the NAT attributes to operationalize with respect to system requirements.

  We conclude we have addressed this aim. We used a process of deduction that enabled us to ascertain that three of 13 NAT attributes can be observed in SCR dependency models of system requirements. Our premise was that NAT attributes could be generalized to linearity where complex systems are nonlinear; simple systems are linear. From this premise, our reasoning led us to identify three NAT attributes to operationalize: interconnectivity, common-mode connections, and multiple control parameters.

- Specific Aim 2: Identify a formal modeling method for system requirements that will afford quantification of the potential metrics.

  We conclude the SCR models and simulations successfully served our research needs so, this aim was satisfied. We have shown that the formal system model created with the SCR tool is useful for modeling, simulating, and analyzing human-computer interactions in the context of NAT. The SCR dependency graphs accommodated multiple levels of system abstraction and multiple projections needed for specific aim 3. Secondly, the SCR toolset successfully supported simulation of our model. A PC-based GUI for the simulation was created using SCR simulation tools. Volunteer subjects were able to quickly learn (in about 10 minutes) to run the simulation and effectively understand the simulation such that useful data were collected.

- Specific Aim 3: Identify potential metrics for each NAT attribute to be operationalized. At least one metric, and ideally four metrics, should be identified for each of these NAT attributes.

  We conclude that this aim was satisfied as evidenced by 15 metrics proposed to measure or indicate the three NAT attributes from specific aim 1. We infer a degree of validity to the proposed metrics because our selection process addressed the limitations of NAT and of other metric research, and our selection process addressed the multidimensional aspects of complexity. We used multiple system abstractions and multiple perspectives to obtain our metrics. Three levels of system abstraction formed a hierarchy of SCR dependency graphs that modeled system requirements in increasing detail. For each abstraction, we applied a projection from the system's input environment, from the output environment of system behaviors visible to humans interacting with the system, and from a collective projection of all the system's internal dependencies. This process was an effort to address the multidimensional aspects of complexity.

- Specific Aim 4: Determine which, if any of the potential metrics operationalize the NAT attributes for system requirements.

  We conclude this aim was satisfied. This is evidenced by data obtained from hypotheses testing and the steps to reduce internal validity threats. Hypotheses test results showed five out of the 15 proposed metrics had structure correlations exceeding .25, standard errors of less than .10, and statistically significant confidence intervals.

Conclusion 2

We conclude the research is not without limitations; additional research is needed to address these limitations and to advance our knowledge. This conclusion is based on four research limitations.

- Predictive limitations: The research did not develop mathematical models and inference procedures to identify and assign a probability to future outcomes. More specifically, this research did not establish benchmarks for the complexity metrics; so one cannot make predictions based solely on the metric values.

- NAT operalization limitations: We have operationalized three NAT attributes: interconnectivity, common-mode connections, and multiple, interacting control parameters. This is a small subset; thus, the research is limited to a narrow segment of the 13 NAT attributes of NAT.

- Limited subject diversity: The data from our volunteer subject characterizations indicates a relatively homogenous group of people. The potential exists that subjects had similar perceptions because of the homogenous makeup of the group.

Therefore, this can potentially be a threat to external validity with respect to generalizations to other populations.

- Unknown external validity: This section addresses generalization to other systems. The resulting set of independent variables *X13*, *X7*, *X5*, *X2*, and *X6* and the rejection of the null hypotheses were based on statistically significant test results specific to the data set. It is not known if these independent variables are useful for other systems, or if the same inferences concerning the six research hypotheses would pertain to other systems. More empirical research is needed to determine external validity.

Future Work

Predictive system research

The research has limitations for use as a predictive tool or system. Much empirical research is needed to develop accurate models and inference procedures so that NAT complexity-related hazards can be identified and predicted. Probabilistic mathematical models are needed as well as a large body of empirical data.

External validity

Thirty-two volunteer subjects were used in this research. This is a limited group in terms of the quantity and the homogenous make-up of subjects. Therefore, more empirical research needed study other populations and other computer-based systems.

NAT attribute completeness

Perrow theorized that accidents are inevitable in complex, tightly coupled technological systems (Perrow, 1999). He characterized complex systems by describing thirteen attributes. Our research suggests there attributes missing from Perrow's list of thirteen attributes of complex systems. We theorize that multiple modes of system operation are also a NAT attribute. The hazards associated with complex, multi-mode systems are documented and research has begun (Degani, 1996; Vakil, 2000; Leveson, Pinnel, Sandys, Koga, & Reese, 1997) but the research is not in the context of NAT complexity. Mode confusion is a hazard of multi-mode systems. Mode confusion is exhibited by system behaviors similar to those as seen in our research: the systems become less predictable, observable, and usable to the human.

Concluding Remarks

The major contribution of this work is fundamental to scientific research – to gain knowledge through the discovery of relationship between the variables of interest. Specifically, NAT has been advanced by defining and quantifying complexity measures, and showing their inverse relationship to system predictability, observability, and usability.

This research has taken the first steps to operationalize NAT for computer-based systems. We have also identified and discussed research opportunities that could advance NAT operationalization and the general knowledge base. We trust this research will stimulate and facilitate future research endeavors.

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APPENDIX A
LIGHT CONTROL SYSTEM: PROBLEM DESCRIPTION

The Light Control System: Problem Description (Queins et al., 2000) is reprinted with the permissions of the authors and Professor Hermann Maurer, Editor-in-Chief of the Journal of Universal Computer Science.

Literature Cited

Queins, S., Zimmerman, G., Becker, M., Kronengurg, M., Peper, C., Merz, R., & Schafer, J. (2000). The Light Control Case Study: Problem Description. Journal of Universal Computer Science; Special Issue on Requirements Engineering, Vol. 6, No. 7.

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The Light Control Case Study: *Problem Description*

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Abstract: This document contains a range of needs and requirements concerning the construction of a light control system for a floor of a university building. A description of the building architecture and of some pre-installed (light-)hardware is included. This problem description was the common input for all participants of the requirements engineering case study "Light Control".

Key Words: requirements engineering, building automation, problem description

Introductory Note

This document gives an informal description of the problem "Light Control System", that is the subject of the considered case study. It is based on two previous versions that have been used in the Sonderforschungsbereich 501 "Development of Large Systems with Generic Methods", a large project at the Computer Science Department of the University of Kaiserslautern. The initial version was created in 1995 by Stefan Queins and Gerhard Zimmermann. The second version (reported in [Fe+99]) integrates several changes by Martin Becker and Martin Kronenburg. This version was also used in a Dagstuhl Seminar on "Requirements Capture, Documentation, and Validation" that took place in June 1999.

Finally, the version presented here is the result of repeated revisions by Martin Kronenburg and Christian Peper in agreement with Rolf Merz and Jürgen Schäfer from the Electrical Engineering Department of the University of Kaiserslautern, who were acting as customers in the light control case study (LCCS). Some additional improvements are based on input received from Daniel Berry, Vincenzo Gervasi, Julio Leite, and Vinicius da Silva Almendra.

Thus, the basic intention of providing a customer document as the basis for the case study has been preserved. The revisions were intended to reduce the need for customer feedback during the LCCS. Furthermore, to achieve solutions that are better comparable, all interactions between the customer and the participants of the case study have been published on the web [CF99].

The problem description "Light Control" is divided into 4 parts. [Part 1] is a brief introduction. [Part 2] describes the architecture of the 4th floor of a university building in Kaiserslautern, which is the subject of the informal needs given in [Part 3]. Finally, [Part 4] lists and explains technical terms that are used in the document.

Note that this is a reformatted version of the original LCCS problem description [PD99]. To support the traceability of any references into the original layout, the former page numbers are included here in the format *(n)*. The original paragraph numbering now appears at the end of the paragraphs as [n], most line breaks are preserved.

(3)

1 Introduction

The main motivation for the development of a new light control system are the disadvantages of the currently existing system. Since all lights are controlled manually, electrical energy is wasted by lighting rooms which are not occupied and by little possibilities to adjust light sources relative to need and daylight. [1]

In the following document,

- *keywords* are marked at their first occurrence and listed in the additional dictionary [Part 4]. [2]
- Words written in *emphasis* are names of physical sensors/actuators. [3]
- Paragraphs are numbered for easier reference. [4]

(4)

2 *Floor* Description

In this part, the *architecture* and the *installation* of the given *sensor*s and *actuator*s of Building 32, 4th floor is described. [5]

The fourth *floor* of Building 32 consists of three *section*s and shares two *staircase*s, staircase east (SCE) and staircase west (SCW), with other floors of the building, as shown in Figure 1. *Each* section is divided into some *hallway section*s (H) and *room*s, each of which may be an *office* (O), a *computer lab (*CL), a *hardware lab* (HL), a *peripheral room* (P), or

(5)

a *meeting room* (M). All rooms in a section are accessible via a connected hallway section. There are three hallway sections and 22 rooms to control. [Figure 1] shows also the six *outdoor light sensor*s (*ols1 - ols6*) and the major compass directions. The sensors cover the six directions of the different walls. The label in a room indicates the type of the room and gives a unique number, see [Figure 1]. [6]

2.1 Office Description

Each office (shown in [Figure 2]) has one *door* (d1) to the hallway section and can have up to two doors (d2, d3) leading to its adjacent rooms. Each door is equipped with a *door closed contact*, named *dcc<n>*, where n is the number of the door in the room. [7]

Each office is equipped with [8]

1. one *motion detector* (*imd*), so that the room is fully covered.
2. two *ceiling light group*s (window and wall). The luminaries in a ceiling light group in any room are turned on or off only as a group.
   Each ceiling light group is controlled by one *push button* on the wall (*pb1* and *pb2,* respectively), which toggles the ceiling light group if pushed.

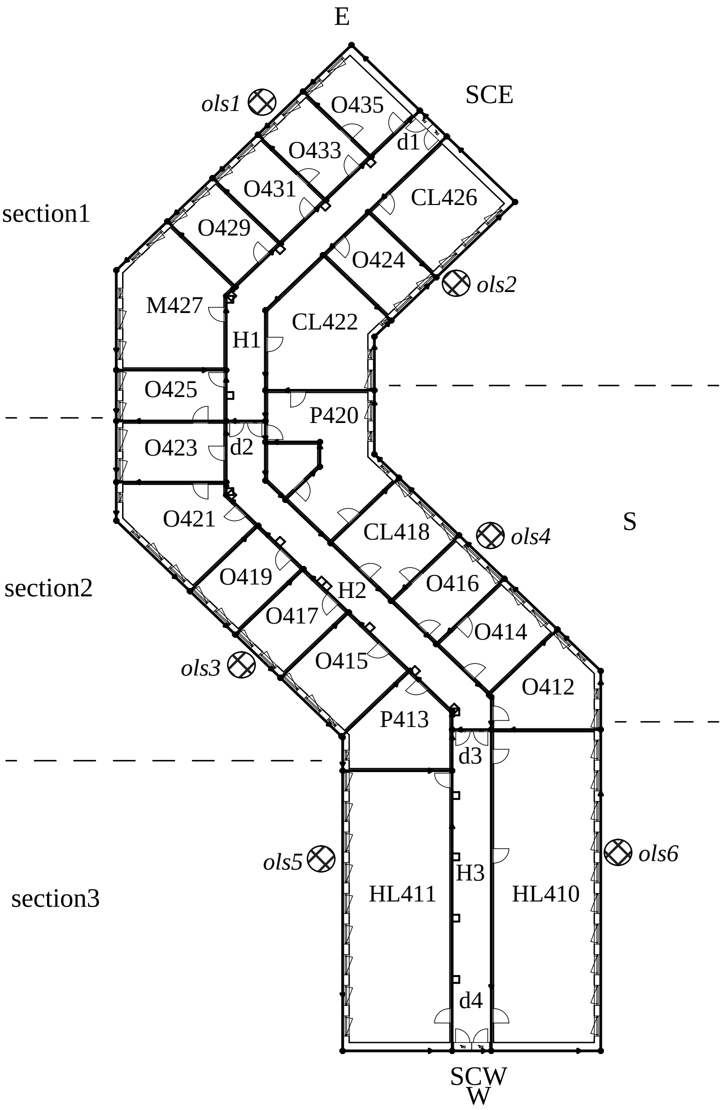


Figure 1: Architecture of the 4th Floor of Building 32

A ceiling light group in a room shows the following behavior if the corresponding push button is pushed:
(i) if the ceiling light group is completely on, it will be switched off
(ii) otherwise it will be switched on completely.

3. Each ceiling light group can be dimmed with its own dimmer-actuator.
4. two *status line*s (*sll1 and sll2*) each of which shows the status of one ceiling light group.

2.2 Computer Lab Description

Same as office. [9]

2.3 Hardware Lab Description

Same as office, but with more than one door leading to the hallway section. [10]

2.4 Meeting Room Description

Same as office. [11]

2.5 Peripheral Room Description

The peripheral rooms will not be controlled by the *control system*, and thus they are not described here! [12]

2.6 Hallway Section Description

Each hallway section is limited by two doors, each of which is leading to an adjacent hallway section or to an adjacent staircase. The associated names of the doors (d1, d2, d3, d4) are shown in Figure 1. Each door is equipped with a door closed contact, named *dcc<n>*, where *n* is derived from the label of the door. [13]

Each hallway section is equipped with [14]

1. two motion detectors (*imd1* and *imd2*), placed above the doors at each end of the hallway section to determine the presence of a person near a door, *(6)*
2. one motion detector to cover the whole section (*imd3*),
3. one *hallway section ceiling light group.* The luminaries in a hallway section ceiling light group are turned on or off only as a group.
   Each ceiling light group is controlled by several push buttons (*pb<i>*) each of which toggles the ceiling light group if pushed.
   A hallway section ceiling light group shows the following behavior if a push button is pushed:
   (i) if the hallway section ceiling light group is on, then it will be switched off
   (ii) otherwise it will be switched on
4. one *status line* (*sll1*) that shows the status of the hallway section ceiling light group.

2.7 Staircase Description

Each staircase connects several floors. [15]

At the landing of each staircase at each floor, the staircase is equipped with [16]

1. one motion detector (*imd1*) above the door of the landing that leads to the adjacent hallway section to detect motion in the staircase near the door.

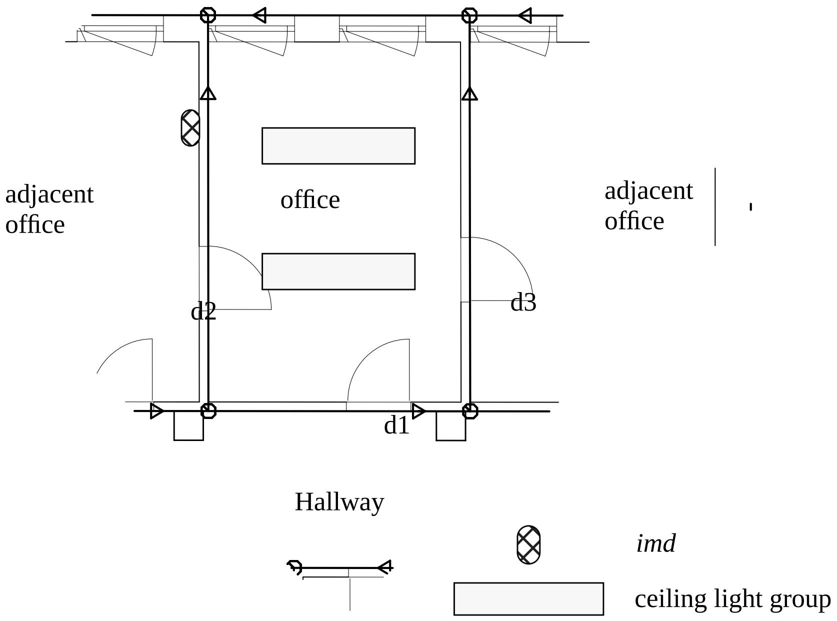


Figure 2: Office Architecture

(7)

2.8 Sensor Description

*Analog sensor*s typically have an exponential response time. Conversion time is the time to convert the analog value to a digital one that can be accessed by the control system. Reaction time is the time from a change of the sensed property to the time when the sensor has reached 90% of the change, excluding conversion time. [17]

Type	Resolution	Range	Reaction Time	Conversion Time	Description
door closed contact		0, 1	10 ms		It is placed above the door and is 1 if the door is fully closed, 0 otherwise
motion detector		0, 1	1 s		If set to 1, a person is moving, even very slowly, in the range of the detector.
status line		0, 1	10 ms		Senses if the light voltage is turned on (1) or off (0).
outdoor light sensor	1 lux	1-10000 lux	10 ms	1 s	Mounted perpendicular to facade, measures the *illumination* of the facade for the calculation of light flow through a window.

Table 1: Sensors

2.9 Actuator Description

Actuators have a linear response time. Reaction time is therefore defined as the time to change from 0 to 100% respectively 100 to 0%, if different. [18]

Type	Range	Control	Reaction Time	Description
control system active		0, 1	10 ms	If the control system sends a 1 within every 60 s, the control system is still alive.
dimmer	0-100%		10 ms	Controls light between 0 (off) and 10-100% (on).
pulse	0, 1		10 ms	If the value changes from 0 to 1, the light changes from on to off or from off to on.
push button		0, 1	10 ms	1 as long as pushed

Table 2: Actuators

(8)

2.10 Dimmable Light

The structure of a *dimmable light* is shown in [Fig. 3]. Inputs to a dimmable light are created by a *pulse* to toggle the light, by a *dimmer* to set the current dim value, and by *control system active* to show the status of the control system. If this signal is not sent every 60 s, the dimmable light switches to fail safe mode, i.e. dim value is assumed to be 100%. Outputs of a dimmable light are generated by a *status line* to show the current state (on or off) of the light: [19]

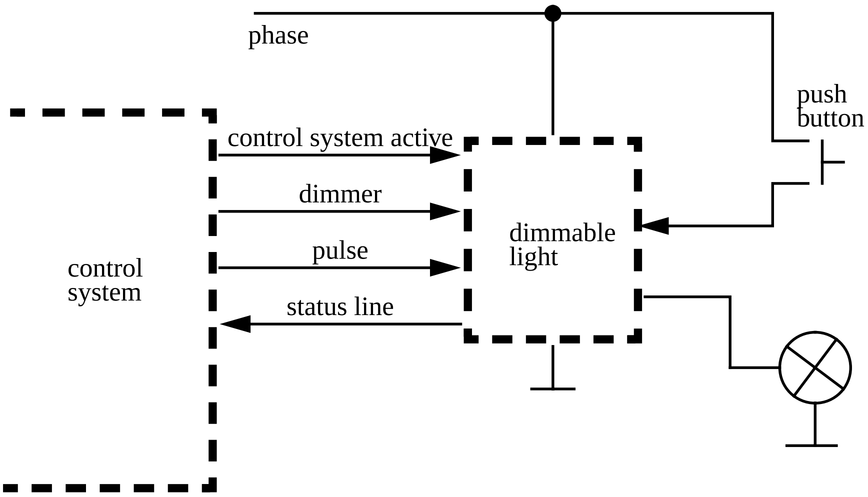


Figure 3: Dimmable Light

3 Informal Needs

(9)

This part contains the needs for a new light control system for the fourth floor of Building 32 of the University of Kaiserslautern. [20]

In [Sec. 3.1], functional needs are listed and in [Sec. 3.2] non-functional needs are listed. [21]

3.1 Functional Needs

The functional needs are split into two groups, *user* needs and *facility manager* needs, depending on the person who has expressed them. [22]

3.1.1 User Needs

The user needs are labelled by U<number>. [23]

At first, general user needs are listed, which are demanded for each kind of room: [24]

U1 If a person occupies a room, there has to be *safe illumination*, if nothing else is desired by the *chosen light scene*.

U2 As long as the room is occupied, the chosen light scene has to be maintained.

U3 If the room is reoccupied within T1 minutes after the last person has left the room, the chosen light scene has to be reestablished.

U4 If the room is reoccupied after more than T1 minutes since the last person has left the room, the *default light scene* has to be established.

U5 For each room, the chosen light scene can be set by using the *room control panel*.

U6 For each room, the default light scene can be set by using the room control panel.

U7 For each room, the value T1 can be set by using the room control panel.

U8 If any outdoor light sensor or the motion detector of a room does not work correctly, the user of this room has to be informed.

U9 The room control panel for an office should contain at least:
(i) a possibility to set each ceiling light group
(ii) a possibility to set the chosen and the default light scene
(iii)a possibility to set T1

The user needs concerning the offices are: [25]

U10 The ceiling light groups should be maintained by the control system depending on the *current light scene*.

U11 A room control panel in an office should be movable as is a telephone.

The user needs for the remaining rooms are: [26]

U12 In all other rooms, the room control panel should be installed near a door leading to the hallway section.

The user needs for the hallway sections are: [27]

U13 When a hallway section is occupied by a person, there has to be safe illumination.

U14 Before a person enters one hallway section from another one or from a staircase, the hallway section ceiling light group in the section being entered has to be on.

3.1.2 Facility Manager Needs

(10)

The facility manager needs are labelled by FM<number>.[28]

FM1 Use daylight to achieve the *desired light setting* of each room and each hallway section whenever possible.

FM2 The ceiling light group in each hallway section has to be off when the hallway section has been unoccupied for at least T2 minutes.
FM3 The ceiling light groups in a room have to be off when the room is unoccupied for at least T3 minutes.
FM4 For each hallway section, the value T2 can be set by using the *facility manager control panel*.
FM5 For each room, the value T3 can be set by using the facility manager control panel.
FM6 The facility manager can turn off the ceiling light groups in a room or hallway section that is not occupied.
FM7 If a *malfunction* occurs, the facility manager has to be informed.
FM8 If a malfunction occurs, the control system supports the facility manager in finding the reason.
FM9 The system provides reports on current and past energy consumption.
FM10 All malfunctions and unusual conditions are stored and reported on request.
FM11 Malfunctions that the system cannot detect can be entered manually.

3.2 Non-Functional Needs

The non-functional needs are split into several groups according to the aspect they are dealing with. They are labelled by NF<number>. [29]

3.2.1 Fault Tolerance

In any case of failure, the system shall provide a stepwise degradation of functionality down to manual operability. [30]

Needs in the case of a malfunction of the outdoor light sensor: [31]

NF1 If any outdoor light sensor does not work correctly, the control system for rooms should behave as if the outdoor light sensor had been submitting the last correct measurement of the outdoor light constantly.
NF2 If any outdoor light sensor does not work correctly, the default light scene for all rooms is that all ceiling light groups are on.
NF3 If any outdoor light sensor does not work correctly and a hallway section is occupied, the ceiling light group in this hallway section has to be on.

Needs in the case of a malfunction of the motion detector: [32]

NF4 If any motion detector of a room or a hallway section does not work correctly, the control system should behave as if the room or the hallway section were occupied.

Needs in a worst-case failure of the control system: [33]

NF5 If the ceiling light group in a hallway section is controllable neither automatically nor manually, the ceiling light group of this hallway section has to be on.

3.2.2 Safety and Legal Aspects

NF6 All hardware connections are made according to DIN standards.
NF7 No hazardous conditions for persons, inventory, or building are allowed.

3.2.3 User Interface

NF8 The control panels are easy and intuitive to use.
NF9 The system issues warnings on unreasonable inputs.

4 Dictionary of Terms

Keyword	Description
actuator	device that can be used by the control system to control an environmental quantity
ambient light level	illumination in a room
analog sensor	a sensor that measures an analog value
architecture	structure of a building, floor, or room
ceiling light group	luminary under or in the ceiling,
chosen light scene	a *light scene* chosen by a user using the room control panel for the case that a room is occupied
computer lab	room with a pool of terminals and workstations, open to all users and temporarily to students of a class
control panel	small device with a keyboard, LEDs for important states, and a simple display for textual messages
control system	hard- and software system that controls indoor climate, lighting, safety and security
current light scene	the light scene currently established by the control system
default light scene	a light scene for the case that a room is not occupied
desired light setting	the setting of a ceiling light group in a room or a hallway section desired by the control system
dimmable light	luminary that can be dimmed
dimmer-actuator	actuator controlling the output of a luminary
door	connection between rooms and hallway sections
door closed contact	electrical or magnetic gadget to determine the state of a door
facility manager	person responsible for running a building on a daily basis
facility manager control panel	a control panel for the facility manager
floor	part of a building
hallway section	part of a section between several rooms to connect them to each other
hallway sections ceiling light group	ceiling light group in a hallway section
hardware lab	room with terminals and other electronic devices
illumination	amount of light falling on a surface, measured in lux

Table 3: Dictionary of terms of the application domain

Keyword	Description
installation	equipment belonging to a building
light scene	a light scene is a predefined setting of the ambient light level and a prescription that determines in which way the ceiling light groups should be used to achieve this ambient light level. A light scene is given by: 1. name of the light scene 2. the desired ambient light level in a room 3. one of the following three options: window, wall, both window means that at first the ceiling light group near the window should be used to achieve the desired ambient light level and then the other ceiling light group wall means that at first the ceiling light group near the wall should be used to achieve the desired ambient light level and then the other ceiling light group both means that both ceiling light groups should be used equally to achieve the desired ambient light level
malfunction	incorrect behavior of a device
meeting room	a room open to all users
motion detector	sensor detecting motion of a person or animal in its range, state is on during positive detection
office	room for one or two users with terminals and/or workstations
outdoor light sensor	sensor measuring the illumination in a half sphere perpendicular to its flat bottom
peripheral room	room for computer peripherals, copy machines; open to all users
push button	an actuator for switching on and off a ceiling light group; it is on, as long as pushed manually
room	part of a section
room control panel	a control panel in a room
safe illumination	illumination greater than 14 lux
section	part of a floor
sensor	device that can sense something
staircase	part of a building connecting several floors
status line	wire that has the status of a device as value
user	person occupying a room or a hallway section

Table 3: Dictionary of terms of the application domain, cont.

References

[Fe+99] R. L. Feldmann, J. Münch, S. Queins, S. Vorwieger, G. Zimmermann: *Baselining a Domain-Specific Software Development Process*, Technical Report SFB501 TR-02/99, University of Kaiserslautern, 1999

[PD99] *The Light Control Case Study: Problem Description*, original version at http://rn.informatik.uni-kl.de/~recs/problem/, University of Kaiserslautern, 1999

[CF99] *Customer Feedback of the LCCS*, http://rn.informatik.uni-kl.de/~recs/qna/, University of Kaiserslautern, 1999

APPENDIX B
SCR SPECIFICATION FILE

Appendix B lists the SCR specifications for treatment B of the wall and window light pushbutton scenario; this serves as an example of an SCR specification for a given scenario. SCR specifications were also created for each treatment (A and B) for each of the three scenarios. This resulted in creating six SCR specifications. The following SCR specification is based on the file dinreqout.ssl created by the Navel Research Laboratory (NRL Heitmyer).

```
// This is the SCR specification file for the wall and window light
pushbutton scenario, treatment B. It is based on the NRL dinreqdout.ssl
specification. J. Sammarco identified three specification errors and
collaborated with T. Grimm for the corrections. T. Grimm implemented
three changes:

1. mIndoorLL made to use the new value of iOLS instead
   of the old value (a prime was added to the asignement)
   \ "Light Control Example: mIndoorLL value is set to old iOLS value\"

2. The tNeverOccupied term was added and used in the
   tCurrentLSOpt and tCurrentLSVal functions to make it
   properly use the default settings for the first occupant
   even though the duration result shortly after the
   initial state is not yet at or beyond mT1 (in other words
   it assumes the room has been unoccupied starting in the initial
   state). \"Light Control Example: Duration Initial State Issue\"

3. Add WHEN (NOT iMD) to the end of the second event expression,
preventing the error in both cited cases of resetting the room to
unoccupied when it really is occupied.
   \"Light Control Example: Another Duration Initial State
    Problem plus a Related Problem\"

J Sammarco implemented additional changes for the scenario:

1) oWallOuput and oWindowOutput terms created for display purposes.
Display = 0 if pulse is off.  This reduces confusion because prior
version displayed oDimmerWall & oDimmerWindow at some value even though
oPulseWall and oPulseWindow were off.

2) Pushbutton behavior changed to behave like traditional dimmer switch
Changes to oPulseWall & oPulseWindow";


// This section contains all of the items in the
// Type Dictionary.
TYPE "yAmbientLevel";   BASETYPE "Integer";     UNITS "n.a.";
            VALUES "[0,100]";
  COMMENT "In %";
TYPE "yLight";    BASETYPE "Enumerated";  UNITS "n.a.";
            VALUES "off, on";
TYPE "yLightLevel";     BASETYPE "Integer";     UNITS "n.a.";
            VALUES "[0,10000]";
  COMMENT "in lux";
TYPE "yMalfcnLight";    BASETYPE "Enumerated";  UNITS "n.a.";
            VALUES "green, red";
  COMMENT "red indicates a malfunction";
TYPE "yOption";   BASETYPE "Enumerated";  UNITS "n.a.";
            VALUES "wall, window, both";
  COMMENT "Light scene options";
TYPE "yTimer";    BASETYPE "Integer";     UNITS "n.a.";
            VALUES "[0,30]";
  COMMENT "in minutes";


// Mode Class Dictionary.
```

```
MODECLASS "mcStatus";   MODES "unoccupied, occupied,\ntemp_empty";
            INITMODE "unoccupied";


// Constant Dictionary.
// none


// Variable Dictionary.
TERM "cMDmalfunction";  TYPE "yMalfcnLight";    INITVAL "green";
            ACCURACY "n.a.";
TERM "cOLSmalfunction"; TYPE "yMalfcnLight";    INITVAL "green";
            ACCURACY "n.a.";
TERM "cWallLL";   TYPE "yLightLevel";     INITVAL "0";
            ACCURACY "n.a.";
TERM "cWallLights";     TYPE "yLight";    INITVAL "off";
            ACCURACY "n.a.";
TERM "cWindowLL"; TYPE "yLightLevel";     INITVAL "0";
            ACCURACY "n.a.";
TERM "cWindowLights";   TYPE "yLight";    INITVAL "off";
            ACCURACY "n.a.";
MON "iChosenLSOpt";     TYPE "yOption";   INITVAL "wall";
            ACCURACY "n.a.";
MON "iChosenLSVal";     TYPE "yLightLevel";     INITVAL "200";
            ACCURACY "n.a.";
MON "iDCC"; TYPE "Boolean";   INITVAL "FALSE";  ACCURACY
      "n.a.";
MON "iDefLSOpt";  TYPE "yOption";   INITVAL "wall";
            ACCURACY "n.a.";
MON "iDefLSVal";  TYPE "yLightLevel";     INITVAL "100";
            ACCURACY "n.a.";
MON "iFMOverride";      TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
MON "iMD";  TYPE "Boolean";   INITVAL "FALSE";  ACCURACY "n.a.";
MON "iMDmalfunction";   TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
MON "iOLS"; TYPE "yLightLevel";     INITVAL "0";      ACCURACY
      "n.a.";
MON "iOLSmalfunction";  TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
MON "iSLLWall";   TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
MON "iSLLWindow"; TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
MON "iT1";  TYPE "yTimer";    INITVAL "10";     ACCURACY "n.a.";
MON "iT3";  TYPE "yTimer";    INITVAL "15";     ACCURACY "n.a.";
TERM "mChosenLSOpt";    TYPE "yOption";   INITVAL "wall";
            ACCURACY "n.a.";
TERM "mChosenLSVal";    TYPE "yLightLevel";     INITVAL "200";
            ACCURACY "n.a.";
TERM "mDefLSOpt"; TYPE "yOption";   INITVAL "wall";
            ACCURACY "n.a.";
TERM "mDefLSVal"; TYPE "yLightLevel";     INITVAL "100";
            ACCURACY "n.a.";
TERM "mFMOverride";     TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
TERM "mIndoorLL"; TYPE "yLightLevel";     INITVAL "0";
```

```
            ACCURACY "n.a.";
TERM "mMDmalfunction";  TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
TERM "mOLSmalfunction"; TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
TERM "mOccupied"; TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
TERM "mT1"; TYPE "yTimer";    INITVAL "10";     ACCURACY "n.a.";
TERM "mT3"; TYPE "yTimer";    INITVAL "15";     ACCURACY "n.a.";
TERM "mWallLights";     TYPE "yLight";    INITVAL "off";
            ACCURACY "n.a.";
TERM "mWindowLights";   TYPE "yLight";    INITVAL "off";
            ACCURACY "n.a.";
CON "oDimmerWall";      TYPE "yAmbientLevel";   INITVAL "0";
            ACCURACY "n.a.";
CON "oDimmerWindow";    TYPE "yAmbientLevel";   INITVAL "0";
            ACCURACY "n.a.";
CON "oMDmalfunction";   TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
CON "oOLSmalfunction";  TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
CON "oPulseWall"; TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
CON "oPulseWindow";     TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
CON "oWallOutput";      TYPE "yAmbientLevel";   INITVAL "0";
            ACCURACY "n.a.";
CON "oWindowOutput";    TYPE "yAmbientLevel";   INITVAL "0";
            ACCURACY "n.a.";
TERM "tCurrentLSOpt";   TYPE "yOption";   INITVAL "wall";
            ACCURACY "n.a.";
TERM "tCurrentLSVal";   TYPE "yLightLevel";     INITVAL "100";
            ACCURACY "n.a.";
TERM "tNeverOccupied";  TYPE "Boolean";   INITVAL "TRUE";
TERM "tOverride"; TYPE "Boolean";   INITVAL "FALSE";
            ACCURACY "n.a.";
TERM "tRemLL";    TYPE "yLightLevel";     INITVAL "0";
            ACCURACY "n.a.";
MON "time"; TYPE "Integer";   INITVAL "0";      ACCURACY "n.a.";


// Assertion Dictionary.
// none

// Assumption Dictionary.
// none

// Enumerated Monitored Variable Table.
// none


// This section contains the event, mode transition, and condition
functions.

CONDFUNC "cMDmalfunction";
      CONDITIONS "NOT mMDmalfunction",    "mMDmalfunction";
            ASSIGNMENTS "green",    "red";
```

```
CONDFUNC "cOLSmalfunction";
      CONDITIONS "NOT mOLSmalfunction",   "mOLSmalfunction";
            ASSIGNMENTS "green",    "red";

CONDFUNC "cWallLL";
      CONDITIONS "tCurrentLSOpt = both",
      "tCurrentLSOpt = wall AND tRemLL > 5000",
      "tCurrentLSOpt = wall AND tRemLL <= 5000",
      "tCurrentLSOpt = window AND tRemLL > 5000",
      "tCurrentLSOpt = window AND tRemLL <= 5000";
            ASSIGNMENTS "tRemLL / 2",     "5000",     "tRemLL",
      "tRemLL - 5000",  "0";

EVENTFUNC "cWallLights";
      EVENTS "@T(mWallLights = on) WHEN (cWallLights = off) OR
@T(mcStatus = occupied)",
      "@T(mWallLights = off) WHEN (cWallLights = on) OR @T(mcStatus =
unoccupied) OR\n@T(mFMOverride) WHEN (NOT (mcStatus = occupied))";
            ASSIGNMENTS "on", "off";

CONDFUNC "cWindowLL";
      CONDITIONS "tCurrentLSOpt = both",
      "tCurrentLSOpt = wall AND tRemLL > 5000",
      "tCurrentLSOpt = wall AND tRemLL <= 5000",
      "tCurrentLSOpt = window AND tRemLL > 5000",
      "tCurrentLSOpt = window AND tRemLL <= 5000";
            ASSIGNMENTS "tRemLL / 2",     "tRemLL - 5000",  "0",
      "5000",     "tRemLL";

EVENTFUNC "cWindowLights";
      EVENTS "@T(mWindowLights = on) WHEN (cWindowLights = off) OR
@T(mcStatus = occupied)",
      "@T(mWindowLights = off) WHEN (cWindowLights = on) OR @T(mcStatus
= unoccupied) OR @T(mFMOverride) WHEN (NOT (mcStatus = occupied))";
            ASSIGNMENTS "on", "off";

CONDFUNC "mChosenLSOpt";
      CONDITIONS "true";
            ASSIGNMENTS "iChosenLSOpt";

CONDFUNC "mChosenLSVal";
      CONDITIONS "true";
            ASSIGNMENTS "iChosenLSVal";

CONDFUNC "mDefLSOpt";
      CONDITIONS "NOT iOLSmalfunction",   "iOLSmalfunction";
            ASSIGNMENTS "iDefLSOpt",      "both";

CONDFUNC "mDefLSVal";
      CONDITIONS "NOT iOLSmalfunction",   "iOLSmalfunction";
            ASSIGNMENTS "iDefLSVal",      "10000";

CONDFUNC "mFMOverride";
      CONDITIONS "true";
            ASSIGNMENTS "iFMOverride";
```

```
EVENTFUNC "mIndoorLL";
      EVENTS "@C(iOLS) WHEN (NOT iOLSmalfunction)";
            ASSIGNMENTS "iOLS'";
  DESCRIPTION "NOTE:  This should be a function of iOLS, but we cannot
denote functions!!!";


CONDFUNC "mMDmalfunction";
      CONDITIONS "true";
            ASSIGNMENTS "iMDmalfunction";

CONDFUNC "mOLSmalfunction";
      CONDITIONS "true";
            ASSIGNMENTS "iOLSmalfunction";

EVENTFUNC "mOccupied";
      EVENTS "@T(iMD) OR @T(iMDmalfunction)",
      "@F(iMD) when ((NOT iDCC OR (duration(iDCC AND iMD) < 1))\nAND
NOT iMDmalfunction) OR @T(duration(NOT iMDmalfunction) >= 2)\n    WHEN
(NOT iMD)";
            ASSIGNMENTS "true",     "false";
CONDFUNC "mT1";
      CONDITIONS "true";
            ASSIGNMENTS "iT1";

CONDFUNC "mT3";
      CONDITIONS "true";
            ASSIGNMENTS "iT3";

CONDFUNC "mWallLights";
      CONDITIONS "iSLLWall",  "NOT iSLLWall";
            ASSIGNMENTS "on", "off";

CONDFUNC "mWindowLights";
      CONDITIONS "iSLLWindow",      "NOT iSLLWindow";
            ASSIGNMENTS "on", "off";

MODETRANS "mcStatus";
  FROM "unoccupied"     EVENT "@T(mOccupied)"   TO "occupied";
  FROM "occupied" EVENT "@F(mOccupied)"   TO "temp_empty";
  FROM "temp_empty"     EVENT "@T(duration(NOT mOccupied) > mT3)"
            TO "unoccupied";
  FROM "temp_empty"     EVENT "@T(mOccupied)"   TO "occupied";

CONDFUNC "oDimmerWall";
      CONDITIONS "TRUE";
            ASSIGNMENTS "cWallLL/50";

CONDFUNC "oDimmerWindow";
      CONDITIONS "true";
            ASSIGNMENTS "cWindowLL/50";

CONDFUNC "oMDmalfunction";
      CONDITIONS "cMDmalfunction = green",      "cMDmalfunction = red";
            ASSIGNMENTS "false",    "true";

CONDFUNC "oOLSmalfunction";
```

```
      CONDITIONS "cOLSmalfunction = green",     "cOLSmalfunction =
red";
            ASSIGNMENTS "false",    "true";

EVENTFUNC "oPulseWall";
      EVENTS "@T(cWallLights = on) AND (NOT iSLLWall') OR
@T(cWallLights = off) AND iSLLWall'",
      "@C(iSLLWall) AND (cWallLights' = off) ",
      "@C(iSLLWall) AND (cWallLights' = on) ";
            ASSIGNMENTS "true",     "true",     "false";

EVENTFUNC "oPulseWindow";
      EVENTS "@T(cWindowLights = on) AND (NOT iSLLWindow') OR
@T(cWindowLights = off) AND iSLLWindow'",
      "@C(iSLLWindow) AND (cWindowLights' = off) ",
      "@C(iSLLWindow) AND (cWindowLights' = on) ";
            ASSIGNMENTS "true",     "true",     "false";

CONDFUNC "oWallOutput";
      CONDITIONS "oPulseWall = true",     "oPulseWall = false";
            ASSIGNMENTS "oDimmerWall",    "0";

CONDFUNC "oWindowOutput";
      CONDITIONS "oPulseWindow = true",   "oPulseWindow = false";
            ASSIGNMENTS "oDimmerWindow",  "0";

EVENTFUNC "tCurrentLSOpt";
      EVENTS "@T(mcStatus = occupied) when (tNeverOccupied
OR\n(duration(not(mcStatus = occupied)) >= mT1))",
      "@C(mChosenLSOpt)";
            ASSIGNMENTS "mDefLSOpt",      "mChosenLSOpt'";

EVENTFUNC "tCurrentLSVal";
      EVENTS "@T(mcStatus = occupied) when (tNeverOccupied
OR\n(duration(NOT(mcStatus = occupied)) >= mT1))",
      "@C(mChosenLSVal)";
            ASSIGNMENTS "mDefLSVal",      "mChosenLSVal'";

EVENTFUNC "tNeverOccupied";
      EVENTS "@T(mOccupied)";
            ASSIGNMENTS "FALSE";

EVENTFUNC "tOverride";
      EVENTS "@T(mFMOverride) WHEN (NOT (mcStatus = occupied))",
      "@T(mcStatus = occupied)";
            ASSIGNMENTS "true",     "false";

CONDFUNC "tRemLL";      MCLASS "mcStatus";
  MODES "unoccupied"    CONDITIONS "true",      "false";
  MODES "occupied"      CONDITIONS "mIndoorLL > tCurrentLSVal",
      "mIndoorLL <= tCurrentLSVal";
  MODES "temp_empty"    CONDITIONS "tOverride OR mIndoorLL >
tCurrentLSVal",
      "NOT tOverride AND mIndoorLL <= tCurrentLSVal";
                        ASSIGNMENTS "0",  "tCurrentLSVal-mIndoorLL";
```

Literature Cited

Heitmeyer, C., & Bharadwaj, R (2000). Applying the SCR Requirements Method to the Light Control Case Study. Journal of Universal Computer Science; Special Issue on Requirements Engineering, Vol. 6, No. 7.

APPENDIX C
INSTITUTIONAL REVIEW BOARD EXEMPTION

Chairperson
Institute Review Board
West Virginia University

February 11, 2002

Dear Chairperson:

I am requesting Institute Review Board exemption for my experiments using human subjects. These experiments are part of my Ph.D. study "A Complexity Assessment Methodology for Safety-Critical, Embedded Systems". My committee chair and faculty advisor is Dr. Roy Nutter from the department of Computer Science and Electrical Engineering (CSEE).

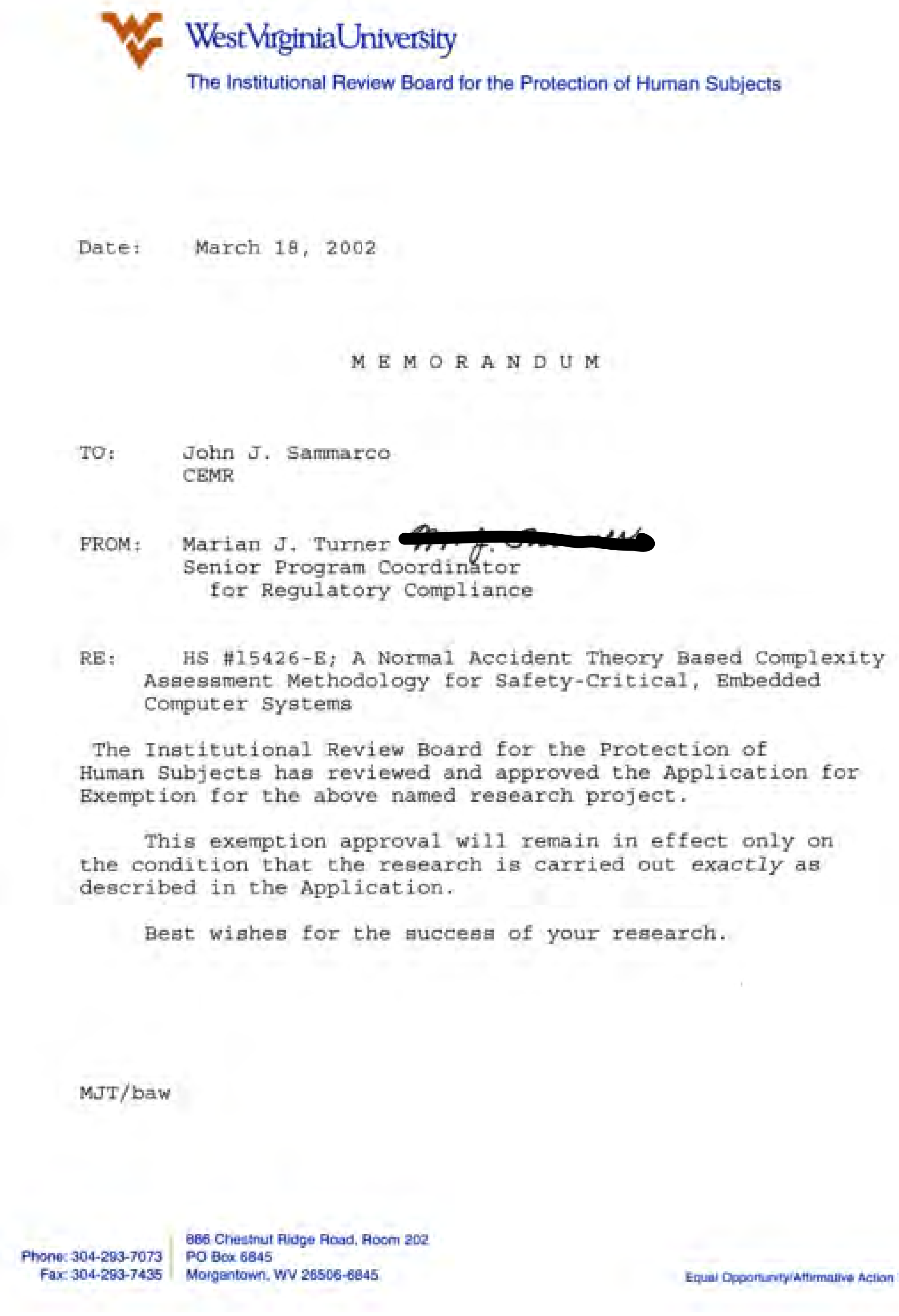
My research involves surveys of subjects. The identity of each subject will not be recorded or revealed; thus, I believe this research belongs to category 5 of the A criteria for exemption from board review.

The research includes experiments with subjects from private industry. Subjects will use a PC-based simulation and provide feedback concerning their perceptions of system predictability, complexity, and usability.

Attached please find:
1) Application for Exemption
2) Sample subject cover letter

Sincerely,

John J. Sammarco, PE



WestVirginiaUniversity

The Institutional Review Board for the Protection of Human Subjects

Date: March 18, 2002

MEMORANDUM

TO: John J. Sammarco
CEMR

FROM: Marian J. Turner [redacted]
Senior Program Coordinator
for Regulatory Compliance

RE: HS #15426-E; A Normal Accident Theory Based Complexity Assessment Methodology for Safety-Critical, Embedded Computer Systems

The Institutional Review Board for the Protection of Human Subjects has reviewed and approved the Application for Exemption for the above named research project.

This exemption approval will remain in effect only on the condition that the research is carried out *exactly* as described in the Application.

Best wishes for the success of your research.

MJT/baw

Phone: 304-293-7073
Fax: 304-293-7435

886 Chestnut Ridge Road, Room 202
PO Box 6845
Morgantown, WV 26506-6845

Equal Opportunity/Affirmative Action

APPENDIX D
SUBJECT QUESTIONAIRE

The subject questionnaire instrument was used to collect data concerning the subject, warm-up test, and test scenarios for treatments A and B. The questionnaire consists of closed-ended questions and open-ended questions. A five-level Likert scale is used for the closed-ended questions.

Appendix D contains the subject questionnaire for those subjects conducting tests in the order defined by phase A. The subject questionnaire for the phase B ordering is not shown, but is identical except that the test scenarios are listed in reverse order.

Subject Questionnaire

The Light Control System (LCS) Study

sequence 1

Part 1: User Profile

1.1 Job Title:

1.2 Age range:

□ 18 - 24

□ 25 - 34

□ 35 - 44

□ 45 - 65^{+}

1.3 Sex:

□ Male

□ Female

1.4 Were you involved in the development of the scenarios?

Yes No

1.5 Rate your knowledge about the light control system.

no knowledge				expert
1	2	3	4	5

1.6 Rate your level of experience in using a PC with Windows.

none				expert
1	2	3	4	5

Please return to the subject instructions and begin the warm-up scenario.

PART 2: Warm-up evaluation

2.1 What is your opinion of the warm-up scenario?

2.1.1 difficult to understand — easy to understand

1 2 3 4 5

2.1.2 frustrating — satisfying

1 2 3 4 5

2.1.3 inadequate control of LCS — adequate control of LCS

1 2 3 4 5

2.1.4 complex — simple

1 2 3 4 5

PC Interface Usability

2.2 What is your opinion of the user interface?

2.2.1 difficult to understand — easy to understand

1 2 3 4 5

2.2.2 inadequate control — adequate control

1 2 3 4 5

2.2.3 complex — simple

1 2 3 4 5

2.3 What is your opinion of the computer screen characters?

hard to read easy to read

1 2 3 4 5

2.4 What is your opinion of the screen layout?

2.4.1 counterintuitive intuitive

1 2 3 4 5

2.4.2 information organization

unclear clear

1 2 3 4 5

2.4.3 information quantity

not enough too much

1 2 3 4 5

2.4.4 information layout

illogical logical

1 2 3 4 5

2.5 Overall, the PC interface is complex to understand

agree disagree

1 2 3 4 5

2.6 Please write any comments. You may use the back of this page.

Please return to the subject instructions and begin the next scenario.

PART 3: Vacant Light Scene

System Predictability

3.1 What is your *initial* opinion of the system's behavior?

3.1.1 confusing understandable

1 2 3 4 5

3.1.2 unpredictable predictable

1 2 3 4 5

3.1.3 unstable stable

1 2 3 4 5

3.2 How difficult is anticipating *the system's* output or behavior?

difficult easy

1 2 3 4 5

System Observability

3.3 Does the system keep you informed about its status or state?

3.3.1 never always

1 2 3 4 5

3.3.2 inappropriately appropriately

1 2 3 4 5

3.4 Recognizing a change in the system's status is

difficult				easy
1	2	3	4	5

3.5 Understanding the meaning or implications of a change in system's status is

difficult				easy
1	2	3	4	5

3.6 Recognizing changes in the display information is

difficult				easy
1	2	3	4	5

System Usability

3.7 The ability to find information is

difficult				easy
1	2	3	4	5

3.8 Can the scenario be performed in a straight-forward manner?

never				always
1	2	3	4	5

3.9 Rate the scenario's complexity.

high				low
1	2	3	4	5

3.10 Please write any comments. You may use the back of this page.

Please return to the subject instructions and begin the next scenario.

PART 4: Lighting Options

System Predictability

4.1 What is your *initial* opinion of the system's behavior?

4.1.1 confusing understandable

1 2 3 4 5

4.1.2 unpredictable predictable

1 2 3 4 5

4.1.3 unstable stable

1 2 3 4 5

4.2 How difficult is anticipating *the system's* output or behavior?

difficult easy

1 2 3 4 5

System Observability

4.3 Does the system keep you informed about its status or state?

4.3.1 never always

1 2 3 4 5

4.3.2 inappropriately appropriately

1 2 3 4 5

4.4 Recognizing a change in the system's status is

difficult easy

1 2 3 4 5

4.5 Understanding the meaning or implications of a change in system's status is

difficult				easy
1	2	3	4	5

4.6 Recognizing changes in the display information is

difficult				easy
1	2	3	4	5

System Usability

4.7 The ability to find information is

difficult				easy
1	2	3	4	5

4.8 Can the scenario be performed in a straight-forward manner?

never				always
1	2	3	4	5

4.9 Rate the scenario's complexity.

high				low
1	2	3	4	5

4.10 Please write any comments. You may use the back of this page.

Please return to the subject instructions and begin the next scenario.

PART 5: Wall and Window Light Push Buttons

System Predictability

5.1 What is your *initial* opinion of the system’s behavior?

5.1.1	confusing				understandable
	1	2	3	4	5
5.1.2	unpredictable				predictable
	1	2	3	4	5
5.1.3	unstable				stable
	1	2	3	4	5

5.2 How difficult is anticipating *the system’s* output or behavior?

	difficult				easy
	1	2	3	4	5

System Observability

5.3 Does the system keep you informed about its status or state?

5.3.1	never				always
	1	2	3	4	5
5.3.2	inappropriately				appropriately
	1	2	3	4	5

5.4 Recognizing a change in the system’s status is

	difficult				easy
	1	2	3	4	5

5.5 Understanding the meaning or implications of a change in system's status is

difficult easy

1 2 3 4 5

5.6 Recognizing changes in the display information is

difficult easy

1 2 3 4 5

System Usability

5.7 The ability to find information is

difficult easy

1 2 3 4 5

5.8 Can the scenario be performed in a straight-forward manner?

never always

1 2 3 4 5

5.9 Rate the scenario's complexity.

high low

1 2 3 4 5

5.10 Please write any comments. You may use the back of this page.

Please return to the subject instructions and begin the next scenario.

PART 6: Lighting Options

System Predictability

6.1 What is your *initial* opinion of the system's behavior?

6.1.1 confusing understandable
1 2 3 4 5

6.1.2 unpredictable predictable
1 2 3 4 5

6.1.3 unstable stable
1 2 3 4 5

6.2 How difficult is anticipating *the system's* output or behavior?
difficult easy
1 2 3 4 5

System Observability

6.3 Does the system keep you informed about its status or state?

6.3.1 never always
1 2 3 4 5

6.3.2 inappropriately appropriately
1 2 3 4 5

6.4 Recognizing a change in the system's status is

difficult				easy
1	2	3	4	5

6.5 Understanding the meaning or implications of a change in the system's status is

difficult				easy
1	2	3	4	5

6.6 Recognizing changes in the display information is

difficult				easy
1	2	3	4	5

System Usability

6.7 The ability to find information is

difficult				easy
1	2	3	4	5

6.8 Can the scenario be performed in a straight-forward manner?

never				always
1	2	3	4	5

6.9 Rate the scenario's complexity.

high				low
1	2	3	4	5

6.10 Please write any comments. You may use the back of this page.

Please return to the subject instructions and begin the next scenario.

PART 7: Vacant Light Scene

System Predictability

7.1 What is your *initial* opinion of the system's behavior?

7.1.1 confusing understandable

1 2 3 4 5

7.1.2 unpredictable predictable

1 2 3 4 5

7.1.3 unstable stable

1 2 3 4 5

7.2 How difficult is anticipating *the system's* output or behavior?

difficult easy

1 2 3 4 5

System Observability

7.3 Does the system keep you informed about its status or state?

7.3.1 never always

1 2 3 4 5

7.3.2 inappropriately appropriately

1 2 3 4 5

7.4 Recognizing a change in the system’s status is

difficult easy

1 2 3 4 5

7.5 Understanding the meaning or implications of a change in system’s status is

difficult easy

1 2 3 4 5

7.6 Recognizing changes in the display information is

difficult easy

1 2 3 4 5

System Usability

7.7 The ability to find information is

difficult easy

1 2 3 4 5

7.8 Can the scenario be performed in a straight-forward manner?

never always

1 2 3 4 5

7.9 Rate the scenario’s complexity.

high low

1 2 3 4 5

7.10 Please write any comments. You may use the back of this page.

Please return to the subject instructions and begin the next scenario.

PART 8: Wall and Ceiling Light Push Buttons

System Predictability

8.1 What is your opinion of the system's behavior?

8.1.1	confusing				understandable
	1	2	3	4	5

8.1.2	unpredictable				predictable
	1	2	3	4	5

8.1.3	unstable				stable
	1	2	3	4	5

8.2 How difficult is anticipating *the system's* output or behavior?

	difficult				easy
	1	2	3	4	5

System Observability

8.3 Does the system keep you informed about its status or state?

8.3.1	never				always
	1	2	3	4	5

8.3.2	inappropriately				appropriately
	1	2	3	4	5

8.4 Recognizing a change in the system's status is

difficult				easy
1	2	3	4	5

8.5 Understanding the meaning or implications of a change in system's status is

difficult				easy
1	2	3	4	5

8.6 Recognizing changes in the display information is

difficult				easy
1	2	3	4	5

System Usability

8.7 The ability to find information is

difficult				easy
1	2	3	4	5

8.8 Can the scenario be performed in a straight-forward manner?

never				always
1	2	3	4	5

8.9 Rate the scenario's complexity.

high				low
1	2	3	4	5

8.10 Please write any comments. You may use the back of this page.

Part 9: Questionnaire Completion

Please write your comments about any aspect of the questionnaire, or any other portion of this experiment. Thank you for participating

APPENDIX E
SUBJECT INSTRUCTIONS

Appendix E contains the subject instructions for those subjects conducting tests in the order defined by phase B. The subject instructions for sequence 1 ordering are not shown, but are identical except that the test scenarios are in reverse order.

Subject Instructions

The Light Control System (LCS) Study

Sequence 2

Preface

This research is being conducted to fulfill the requirements for my doctoral dissertation in Computer Engineering in the Department of Computer Science and Electrical Engineering at West Virginia University. Your participation in this research is voluntary and your identity will not be documented or disclosed.

The purpose of this research is to learn more about what makes a computer-based system complex, as perceived by the user.

This portion of the research involves your running six test scenarios on a simulated computerized office lighting system. Your opinions about the system are given by answering a questionnaire. Also, an observer will take notes as you operate the system.

To become familiar with the lighting system, you will follow instructions for a warm-up session. After the warm-up, you follow instructions to run six pre-defined scenarios for the lighting system. After running each scenario, you are to answer the questionnaire, take a short break, and then begin the next session until the six scenarios are completed.

You are encouraged to verbalize your actions, thoughts and opinions during the experiment.

Thank you for participating.

John J. Sammarco

Experiment Overview

This experiment consists of nine parts. The general process is for you to follow the instructions, answer the questionnaire, and take a one-minute break. The experiment takes about 1 hour to complete.

The experiment uses a light control system (LCS), a fictitious system, as a test vehicle to validate research theories and methodologies. To learn about the LCS you will:

- Watch a short video about the LCS;
- Read a description of the LCS;
- Receive "hands-on" training using the LCS in a warm-up session.

Part 1: User Profile

Please answer the user profile questions, part 1 of the questionnaire. Turn to the next page and read the light control system description once you have completed part 1.

The Light Control System (LCS) Description

The LCS is used to reduce energy costs and help maintain safety. Energy is saved by automatically reducing lighting intensity when the office is empty for extended periods, by enabling users to get the light level they need by adjusting a dimmer instead of using the lights fully on, and by automatically adjusting the lights with respect to sunlight.

The lighting system controls a light near the window and light near the wall as depicted by figure 1. Two sensors provide data to the lighting system. A motion sensor detects if people are in the office; a sunlight sensor measures the office's natural light.

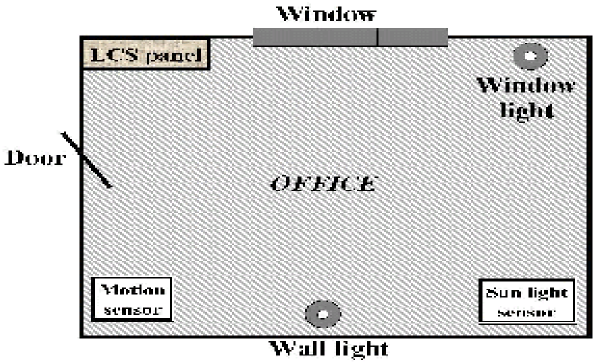
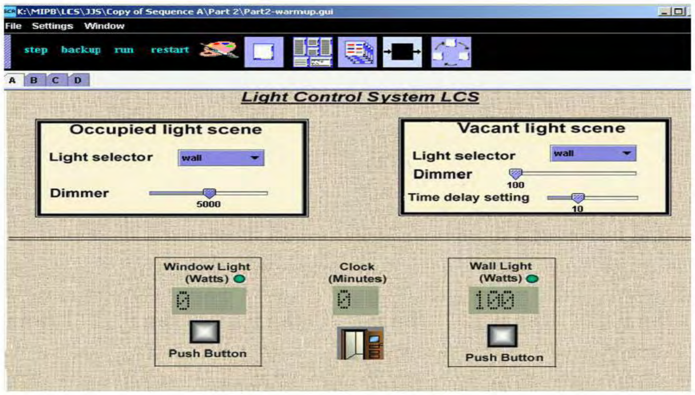


Figure1 – The office layout for the Light Control System

The LCS controls the office lighting for two lighting scenes: occupied and vacant. The occupied light scene is used while a person is in the office. The vacant light scene is used to reduce the lighting when someone leaves the office for an extended period, as set by a time delay. If the person returns to the office *before* the time delay expires, the lighting remains in the occupied light scene. If the person returns *after* the time delay, the vacant light scene is enabled and it will be on when re-entering the office. The vacant and occupied light scenes are controlled with the LCS user-interface panel.

User-Interface Panel:



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Light Control System LCS

Occupied light scene
Light selector: wall
Dimmer: 5000

Vacant light scene
Light selector: wall
Dimmer: 100
Time delay setting: 10

Window Light (Watts): 0
Clock (Minutes): 0
Wall Light (Watts): 100

Figure 2. The graphical user interface.

The LCS graphical user interface, shown by figure 2, is described as follows:

- Occupied Light Scene: The controls consist of a light selector and dimmer. Three light selections are available - wall, window, or both.

- Vacant Light Scene: The controls are the same except for the time delay control.

- LCS Status: The following status information is displayed:

    - Digital displays show the output for each light. No light is produced at 0 watts output; the maximum light is produced at 100 watts output.

    - A digital displays shows elapsed time.

    - Office status is displayed as occupied or vacant.

- Manual Control: Push button switches enable manual control of each light.

Time Simulation

Time is simulated by using the “step” button located at the top of the user-interface panel as depicted by figure 3. This enables time to be advanced one step at a time.

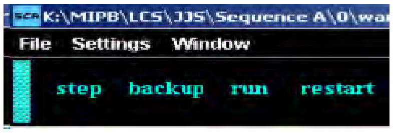

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Figure 3. The SCR Simulator menu for time simulation.

Part 2: Warm up

The warm up helps you to become familiar with the controls and status display. Please read the instructions out loud as you go along and talk about what you observe.

1**)** *Click the door to enter the office; observe both light outputs.*

Notice that the wall light turns on at a reduced default lighting level.

2) The occupied light scene controls enable you to adjust the lighting while you are in the office. Set the occupied light scene as follows:

- *light selector to "both"; this sets the window and wall lights "on"*;
- *dimmer between 3500 and 4500; this value is a measure of light intensity;*

Note: The dimmer value is the **total intensity** as measured in lumen. When the dimmer = 5000 the **total** lighting is 100watts. If the dimmer = 10,000 the **total** lighting is 200 watts. Remember, each light can produce up to 100 watts.

3) Observe the window and wall light outputs. Each light is producing half of the lighting level because both lights are on.

- *dimmer between 2000 and 3000; observe both light outputs;*

4) Set the occupied light scene as follows:

- *light selector to "window"; the window light provides all the lighting;*
- *light selector to "wall"; the wall light provides all the lighting;*
- *dimmer to 0; no lighting is provided;*
- *light selector to "both"; this sets the window and wall lights "on"*;
- *dimmer to 10,000; maximum lighting is provided.*

5) Set the vacant light scene as follows:

- *light selector to "window";*
- *dimmer between 400 and 2000;*
- *time delay setting to 9 minutes.*

Note, if you return to the office *before* the time delay setting of 9 minutes, the lighting will remain in the occupied light scene. If you return *after* the time delay, you will find the vacant light scene on.

6) *Click the door to exit the office.*

Note, the lighting is unchanged because the clock time = 0.

7) You will now simulate being out of the office for 7 minutes.

> *- Using the step button located at the top left of the menu bar, observe both light outputs while slowly advancing time to 7 minutes.*

The lighting is unchanged because time = 7 minutes and this is less than time delay setting of 9 minutes.

8) *Click the door to enter the office.*

The lighting is unchanged because you have returned *before* the time delay.

9) *Click the door to exit the office.*

10) The warm-up is completed; please answer part 2 of the questionnaire.

BREAK

Take a one minute break before starting the next scenario

Part 3: Wall and Window Light Push Buttons

This scenario demonstrates the operation of the light push buttons. You can manually turn the lights off or on by pressing the buttons located beneath the light output displays.

Please read the instructions out loud as you go along and talk about what you observe.

1) *Click the door to enter the office; observe both light outputs.*

It is evening and you need both lights on at high intensity to read a tutorial about new software on your PC. Set the <u>Occupied Light Scene</u> as follows:

- Light selector = both;
- Dimmer = 10000; *observe both light outputs.*

2) You read the tutorial's first part, then decide to try what you have learned. However, the lights are causing computer screen glare. To reduce glare,

- turn the wall light off using the push button; observe both light outputs.
- turn the wall light on using the push button; observe both light outputs.
- turn the window light off using the push button; observe both light outputs.

With the window light off, the glare is reduced so you use your PC.

3) You have finished using the computer and decide to continue reading the tutorial.

Turn the window light on using the push button; *observe both light outputs.*

4) While reading the tutorial, you decide to use only the window light. Set the <u>Occupied Light Scene</u> as follows:

- Dimmer = between 2000 and 2500;
- Light selector = window; observe both light outputs.

5) You are finished working. A friend is waiting in the parking lot to give you a ride. Turn the window light off and on repeatedly by using the push button. This signals your friend that you are ready to leave.

6) Answer the questionnaire.

BREAK

Take a one minute break before starting the next scenario

Part 4: Vacant Light Scene

The vacant light scene is used to reduce the lighting when someone leaves the office for an extended period. If you return to the office *before* the time delay, the lighting is unchanged. If you return *after* the time delay, you will find the vacant light scene on when re-entering the office.

Please read the instructions out loud as you go along and talk about what you observe.

1) *Click the door to enter the office; observe both light outputs.*

It is very dark outside and you decide you need both lights on at full intensity while you work. Set the Occupied Light Scene as follows:

> *- Light selector = both;*
> *- Dimmer = 10,000*; *observe both light outputs.*

2) You are working in the office and want to leave for 5 minutes to get coffee. You set the vacant light scene to save energy and to make sure that you don't return to a totally dark office. Set the Vacant Light Scene as follows:

> *- Light selector = window;*
> *- Dimmer < 2000*;
> *- Time delay setting = 5 minutes.*

3) *Click the door to leave the office; observe both light outputs.*

Note, the lighting is unchanged because time = 0.

4) The door is closed and you are out of the office. You will now simulate returning to the office seven minutes later. This is after the time delay setting of 5 minutes.

> *- While observing both light outputs and the time, use the step button to slowly advance the time to 7* minutes
>
> *- Re-enter the office by clicking the door; observe both light outputs.*

5) Answer the questionnaire.

BREAK

Take a one minute break before starting the next scenario

Part 5: Lighting Options

This scenario demonstrates the operation of the lighting options. The lighting options are wall lights, window lights, or both lights. The lighting options are selected by the user.

Please read the instructions out loud as you go along and talk about what you observe.

1) *Click the door to enter the office; observe both light outputs.*

It is evening and you decide to do some reading while sitting in a chair near the window. Therefore, you will be using the window light. Set the Occupied Light Scene as follows:

- Light selector = window;
- Dimmer = between 2000 - 3000; *observe both light outputs.*

2) Your eyes become tired while reading, so you decide to increase the lighting intensity. Set the Occupied Light Scene as follows:

- *Dimmer = between 4000 - 4800; observe both light outputs.*

The lighting intensity is still too low. Set the Occupied Light Scene as follows:

- Dimmer = between 7000 - 8000; *observe both light outputs.*

3) You have finished reading and decide to work at your desk. You will use the wall light because the desk is close to the wall. Set the Occupied Light Scene as follows:

- Light selector = wall; *observe both light outputs.*

4) The lighting intensity is too high, so set the Occupied Light Scene as follows:

- Dimmer = between 4000 - 4800; *observe both light outputs.*

5) Put both lights on to help keep you alert. Set the Occupied Light Scene as follows:

- Light selector = both;
- Dimmer =10000; observe both light outputs.

6) Answer the questionnaire.

BREAK

Take a one minute break before starting the next scenario

Part 6: Wall and Window Light Push Buttons

This scenario demonstrates the operation of the light push buttons. You can manually turn the lights off or on by pressing the buttons located beneath the light output displays.

Please read the instructions out loud as you go along and talk about what you observe.

1) *Click the door to enter the office; observe both light outputs.*

It is evening and you need both lights on at high intensity to read a tutorial about new software on your PC. Set the Occupied Light Scene as follows:

- Light selector = both;
- Dimmer = 10000; *observe both light outputs.*

2) You read the tutorial's first part, then decide to try what you have learned. However, the lights are causing computer screen glare. To reduce glare,

- turn the wall light off using the push button; observe both light outputs.
- turn the wall light on using the push button; observe both light outputs.
- turn the window light off using the push button; observe both light outputs.

With the window light off, the glare is reduced so you use your PC.

3) You have finished using the computer and decide to continue reading the tutorial.

Turn the window light on using the push button; *observe both light outputs.*

4) While reading the tutorial, you decide to use only the window light. Set the Occupied Light Scene as follows:

- Dimmer = between 2000 and 2500;
- Light selector = window; observe both light outputs.

5) You are finished working. A friend is waiting in the parking lot to give you a ride. Turn the window light off and on repeatedly by using the push button. This signals your friend that you are ready to leave.

6) Answer the questionnaire.

BREAK

Take a one minute break before starting the next scenario

Part 7: Lighting Options

This scenario demonstrates the operation of the lighting options. The lighting options are wall lights, window lights, or both lights. The lighting options are selected by the user.

Please read the instructions out loud as you go along and talk about what you observe.

1) *Click the door to enter the office; observe both light outputs.*

It is evening and you decide to do some reading while sitting in a chair near the window. Therefore, you will be using the window light. Set the Occupied Light Scene as follows:

- *Light selector = window;*
- *Dimmer = between 2000 - 3000*; *observe both light outputs.*

2) Your eyes become tired while reading, so you decide to increase the lighting intensity. Set the Occupied Light Scene as follows:

- *Dimmer = between 4000 - 4800; observe both light outputs.*

The lighting intensity is still too low. Set the Occupied Light Scene as follows:

- *Dimmer = between 7000 - 8000*; *observe both light outputs.*

3) You have finished reading and decide to work at your desk. You will use the wall light because the desk is close to the wall. Set the Occupied Light Scene as follows:

- *Light selector =* wall; *observe both light outputs.*

4) The lighting intensity is too high, so set the Occupied Light Scene as follows:

- *Dimmer = between 4000 - 4800*; *observe both light outputs.*

5) Put both lights on to help keep you alert. Set the Occupied Light Scene as follows:

- *Light selector = both;*
- *Dimmer =10000; observe both light outputs.*

6) Answer the questionnaire.

BREAK

Take a one minute break before starting the next scenario

Part 8: Vacant Light Scene

The vacant light scene is used to reduce the lighting when someone leaves the office for an extended period. If you return to the office *before* the time delay, the lighting is unchanged. If you return *after* the time delay, you will find the vacant light scene on when re-entering the office.

Please read the instructions out loud as you go along and talk about what you observe.

1) *Click the door to enter the office; observe both light outputs.*

It is very dark outside and you decide you need both lights on at full intensity while you work. Set the Occupied Light Scene as follows:

> *- Light selector = both;*
> *- Dimmer = 10,000*; *observe both light outputs.*

2) You are working in the office and want to leave for 5 minutes to get coffee. You set the vacant light scene to save energy and to make sure that you do not return to a totally dark office. Set the Vacant Light Scene as follows:

> *- Light selector = window;*
> *- Dimmer < 2000*;
> *- Time delay setting = 5 minutes.*

3) *Click the door to leave the office; observe both light outputs.*

Note: the lighting is unchanged because time = 0.

4) The door is closed and you are out of the office. You will now simulate returning to the office seven minutes later. This is after the time delay setting of 5 minutes.

> *- While observing both light outputs and the time, use the step button to slowly advance the time to 7* minutes
>
> *- Re-enter the office by clicking the door; observe both light outputs.*

5) Answer the questionnaire.

Part 9: Experiment Completion

This concludes the experiment. Your last step is to answer Part 9 of the questionnaire.

Thank you for participating.

APPENDIX F
OBSERVER INSTRUCTIONS

Observer Instructions

The Light Control System (LCS) Study

Introduction

These instructions provide information useful for your role as an observer. They provide guidance as to what you should or should not do as an observer and a description of the test sequences and procedures.

Observers do multiple tasks. They prepare the tests by loading test files into the PC-based simulator, giving the subjects written instructions and questionnaires, observing and recording the subject's verbal and physical expressions, and collecting the questionnaires.

Each subject will run a test sequence that begins with a warm-up followed by six test scenarios. The warm-up helps the subject become familiar with using the PC-based simulator. The subjects answer a questionnaire after the warm-up and after running each of the tests.

This research uses the Think Aloud protocol. Subjects are encouraged to verbalize what they are doing and thinking during the tests. You, as an observer, are to take notes on verbalization, body language and facial expressions. The data sheets are provided for you.

As an observer, you are not to participate or interact with subjects *while they are running tests*. You may help clarify the subject questions concerning the questionnaire.

Experiment Overview

This experiment uses six test scenarios. The general process is for the subject to:

1. follow the scenario instructions
2. answer the questionnaire
3. take a one-minute break

Note that half of the scenarios are repeated. In other words, there are only three unique scenarios. The scenario names and sequences are listed by Tables 1 and 2.

Table 1: Test sequence 1.

Simulation File	Event File	Comments
Part2-warm-up.sjr	warm-up.ev	warm-up
Part3-VerX-Vac.sjr	Vac.ev	Vacant Light Scene
Part4-Lopt-VerY.sjr	----	Lighting Options
Part5-VerX-Psb.sjr	----	Wall and Ceiling Light Push Buttons
Part6-VerX-Lopt.sjr	----	Lighting Options
Part7-Vac-VerY.sjr	Vac.ev	Vacant Light Scene
Part 8-Psb-VerY.sjr	----	Wall and Ceiling Light Push Buttons

Table 2: Test sequence 2.

Simulation File	Event File	Comments
Part2-warm-up.sjr	warm-up.ev	warm-up
Part3-Psb-VerY.sjr	----	Wall and Ceiling Light Push Buttons
Part4-Vac-VerY.sjr	Vac.ev	Vacant Light Scene
Part5-VerX-Lopt.sjr	----	Lighting Options
Part6-VerX-Psb.sjr	----	Wall and Ceiling Light Push Buttons
Part7-Lopt-VerY.sjr	----	Lighting Options
Part8-VerX-Vac.sjr	Vac.ev	Vacant Light Scene

Test Files

The test files are stored on the network at K:\MIPB\LCS. There is a subfolder for each test sequence. Half of the subjects will run test sequence 1, depicted by table1and the other half will run the test sequence 2, depicted by Table 2. The sequence information is color coded. Sequence A material has a white cover sheet and Sequence B material has a gold-colored cover sheet.

Each test sequence contains up to three files. Files with a ***sjr*** extension are used for the simulation; ***ev*** extension files are event files that enable predefined events to occur during some of the simulations. Lastly, the ***gui*** extension file defines the user interface. The gui file automatically loads when the ***sjr*** simulation file runs.

Observer Procedures

Pre-test Procedures**:**

1. Open the subfolder named “Part 2" and double click the warmup.sjr file.
2. Select “File” from the simulator menu bar shown by figure 1, and select “Clear Events List" to clear any prior information from the simulator.

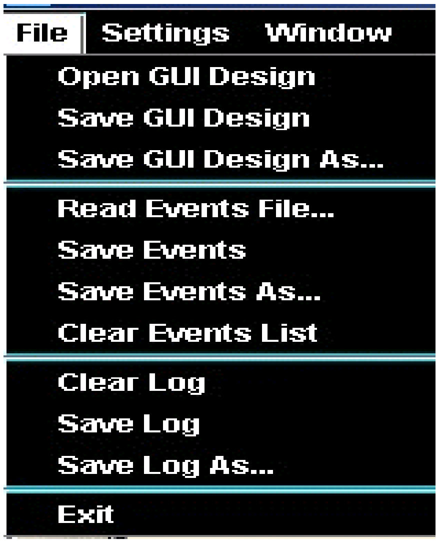

Figure 1 - The SCR simulator file menu.

3. Select “File” from the simulator menu bar and select “Read Events File.” Select *warmup.ev* to load the warm-up scenario events.
4. Load the PowerPoint LCS Description Tutorial.
5. The pretest procedures are completed.

Test Procedures:

1. Thank the subject for participating and let them choose a token of thanks.

2. Read the following to the subject:

You are encouraged to narrate what you are doing and thinking during the tests. I am an observer and will take notes. There are no right or wrong answers to the test. We are interested in your opinions about what you observed during each test.

3. Give the subject the instructions and questionnaire for sequence 1 or 2.

4. Instruct the subject to read the Experiment Overview section of the instructions.

5. Instruct the subject to complete the user profile of part 1in the questionnaire.

6. Play the PowerPoint LCS Description Tutorial for the subject. You may answer questions concerning this tutorial.

7. Play the animated LCS Description Tutorial for the subject. You may answer questions concerning this tutorial.

8. Instruct the subject to read the Light Control System (LCS) Description section of the instructions.

9. Instruct the subject to run the scenario. During the test, record your notes on the data sheet.

10. After the test is completed, instruct subject to answer the Subject Questionnaire.

11. Once the subject finishes the appropriate section of the questionnaire, give the subject a break (at least 1 minute) before starting the next test.

12. While the subject takes a break, load the next ***sjr*** simulation file, clear the events list, and load the ***ev*** event file as needed. The data sheet provides a checklist for these steps.

13. Repeat steps 9-13 for the remaining test scenarios.

Post-test Procedures:

14. Thank the subject for participating.

15. Begin pre-test procedures for the next subject.

APPENDIX G
INDEPENDENT VARIABLE DATA

Table E-1. Independent variable data (*X1* to *X15*) for all scenarios and treatments.

Variable Description	Vacant light scene treatments		Lighting options treatments		Wall and window light pushbutton treatments	
	A	B	A	B	A	B
X1 Cyclomatic complexity	24.0	26.0	14.0	14.0	19.0	19.0
X2 Output cyclomatic complexity	58.0	66.0	20.0	12.0	26.0	12.0
X3 All paths	428.0	495.0	32.0	32.0	78.0	34.0
X4 Graph degree	84.0	84.0	60.0	60.0	74.0	70.0
X5 Critical state changes	14.0	14.0	23.0	14.0	24.0	20.0
X6 In-degree	24.0	23.0	9.0	6.0	6.0	6.0
X7 Out-degree	24.0	23.0	9.0	6.0	8.0	6.0
X8 Cyclomatic complexity	11.0	12.0	2.0	1.0	1.0	1.0
X9 Sheppard complexity metric	11,664.0	279841.0	6561.0	1296.0	2304.0	1296.0
X10 In-degree	3.0	3.0	8.0	8.0	9.0	8.0
X11 Out-degree	14.0	12.0	10.0	10.0	13.0	14.0
X12 Sheppard complexity metric	1764.0	1296.0	6400.0	6400.0	13689.0	12544.0
X13 Input cyclomatic complexity	57.0	62.0	46.0	20.0	54.0	36.0
X14 Output cyclomatic complexity	4.0	6.0	6.0	10.0	10.0	6.0
X15 Vertex unique conditions	7.0	6.0	18.0	16.0	34.0	18.0

APPENDIX H
CURRICULUM VITAE

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Education:

- Ph.D. ABD, Computer Engineering, West Virginia University, 4.0 GPA
- M.S. Computer Engineering, National Technical University
- M.S. Industrial Engineering, University of Pittsburgh
- B.S. Electrical Engineering Technology, Pennsylvania State University

Registration: Professional Engineer, Pennsylvania P.E. No. 32854-E

Membership Activities:

- Vice-Chairperson; Institute of Electrical and Electronic Engineers (IEEE) Committee for Technology Accreditation Activities; Elected position
- Accreditation Evaluator for Computer and Electrical Engineering Technology Programs; Accreditation Board for Engineering and Technology; Term appointment, 1996-2004
- Vice-Chairperson; IEEE Industry Applications Society, Mining Industry Committee; Elected position
- Board Member; MEM Federal Credit Union at Pittsburgh Research Laboratory
- Senior Member, IEEE
- Member, The International System Safety Society

Synopsis of Federal Service:

I am an Electrical Engineer at the National Institute for Occupational Safety and Health (NIOSH), Pittsburgh Research Laboratory. My 16 years of Federal service have been devoted to mine safety research in a wide variety of areas including mining machine navigation and guidance, control systems, sensors, system safety, and hazard and risk analysis. The safety of computerized mining systems has been the focus of my research since 1997. Currently, I am Principal Investigator for a project addressing the safety of programmable electronic systems.

My international recognitions include a National Science Foundation invitation to lecture in India. At the request of the Australian government, I designed and presented two system safety workshops in Australia and gave the key-note address at the 2000 Australian Mine Electrical Safety Seminar. I was a Session Chair at the 2003 International System Safety Conference in Ottawa, Canada.

JOHN J. SAMMARCO, P.E.

Recent Publications:

Sammarco, J. J. (2003). Addressing the Safety of Programmable Electronic Mining Systems: Lessons Learned. 2002 IEEE Industry Applications Conference.

Mowrey, G. L., Fries, E. F., Fisher, T. J., & Sammarco, J. J. (2002). Programmable Electronic Mining Systems: Best Practice Recommendations (In Nine Parts); Part 4: 4.0 Safety File. (Report No. IC 9461). Pittsburgh, PA: NIOSH.

Sammarco, J. J. (2002a). A Complexity Assessment Methodology for Programmable Electronic Mining Systems. The 20th International System Safety Conference.

Sammarco, J. J. (2002b). Programmable Electronic Mining Systems: Best Practice Recommendations (In Nine Parts); Part 3: 3.0 Safety File. (Report No. IC 9461). Pittsburgh, PA: NIOSH.

Sammarco, J. J., & Fisher, T. J. (2001). Programmable Electronic Mining Systems: Best Practice Recommendations (In Nine Parts); Part 2: 2.1 System Safety. (Report No. IC 9458). NIOSH.

Sammarco, J. J., Fisher, T. J., Welsh, J. H., & Pazuchanics, M. J. (2000). Programmable Electronic Mining Systems: Best Practice Recommendations (In Nine Parts); Part 1: 1.0 Introduction. (Report No. IC 9456). Pittsburgh, PA: NIOSH.

Sammarco, J. J., Kohler, J. L., Novak, T., & Morley, L. A. (1997). Safety Issues and the Use of Software-Controlled Equipment in the Mining Industry. Proceedings of IEEE Industry Applications Society 32nd Annual Meeting.

Sammarco, J. J. (1999a). Safety Framework for Programmable Electronics in Mining. Mining Magazine. Society of Mining Engineers.

Sammarco, J. J. (1999b). A Systems Safety Approach for Programmable Electronics, Technology News No. 477. NIOSH

Sammarco, J. J. (1997). Progress in Developing Software Safety Guidelines for the Mining Industry. 4th International Symposium on Mine Mechanization and Automation. Brisbane, Australia

32nd Annual IAS/IEEE Meeting "Safety Issues and the Use of Software-Controlled Equipment in the Mining Industry," J. Sammarco, J. Kohler, T. Novak, and L. Morley, New Orleans, LA, (1997).

4th International Symposium on Mine Mechanization and Automation: "Progress in Developing Software Safety Guidelines for the Mining Industry," Brisbane, Australia, (1997).

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Recent Awards:

Federal Executive Board's Outstanding Professional Employee - Bronze Award 2003

NIOSH Outstanding Performance Award 2003

NIOSH Outstanding Performance Award 1999

NIOSH Performance Award 1998

NIOSH Performance Award 1997

Federal Executive Board's Chairman's Award - Silver Award 1997

Federal Executive Board Outstanding Professional Employee - Silver Award 1995