Summer 2003

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Recommended Citation

Dean, Anthony W.. "A Statistical Evaluation of Risk Priority Numbers in Failure Modes and Effects Analysis Applied to the Prediction of Complex Systems" (2003). Doctor of Philosophy (PhD), dissertation, Engineering Management, Old Dominion University, DOI: 10.25777/yyh5-q645
https://digitalcommons.odu.edu/emse_etds/54

A STATISTICAL EVALUATION OF RISK PRIORITY NUMBERS IN FAILURE MODES AND EFFECTS ANALYSIS APPLIED TO THE PREDICTION OF COMPLEX SYSTEMS

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A Dissertation Submitted to the Faculty of
Old Dominion University in Partial Fulfillment of the
Requirements for the Degree of

DOCTOR OF PHILOSOPHY

ENGINEERING MANAGEMENT

OLD DOMINION UNIVERSITY
August 2003

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ABSTRACT

AN EVALUATION OF RISK PRIORITY NUMBERS IN FAILURE MODES AND EFFECTS ANALYSIS APPLIED TO THE PREDICTION OF COMPLEX SYSTEMS

Anthony W. Dean
Old Dominion University, 2003
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Complex systems such as military aircraft and naval ships are difficult to cost effectively maintain. Frequently, large-scale maintenance of complex systems (i.e., a naval vessel) is based on the reduction of the system to its base subcomponents and the use of manufacturer-suggested, time-directed, preventative maintenance, which is augmented during the systems lifecycle with predictive maintenance which assesses the system's ability to perform its mission objectives. While preventative maintenance under certain conditions can increase reliability, preventative maintenance systems are often costly, increase down time, and allow for maintenance-induced failures, which may decrease the reliability of the system (Ebeling, 1997).

This maintenance scheme ignores the complexity of the system it tries to maintain. By combining the base components or subsystems into a larger system, and introducing human interaction with the system, the complexity of the system creates a unique entity that cannot be completely understood by basing predictability of the system to perform tasks on the reduction of the system to its subcomponents.

This study adds to the scholarly literature by developing a model, based on the traditional failure modes and effects analysis commonly used for research and development projects, to capture the effects of the human interaction with the system. Based on the ability of personnel assigned to operate and maintain the system, the severity of the system failure on the impact on the metasystems ability to perform its mission and the likelihood of the event of the failure to occur.

Findings of the research indicate that the human interaction with the system, in as far as the ability of the personnel to repair and maintain the system, is a vital component in the ability to predict likelihood of the system failure and the prioritization of the risk of system failure, may be adequately captured for analysis through use of expert opinion elicitation. The use of the expert's opinions may provide additional robustness to the modeling and analysis of system behavior in the event that failure occurs.

This work is dedicated to the one person without whom this would not be possible. Sheila, you have been my friend, mentor and confidant. I have learned that I could do anything, or be anything that I dreamed, from you. Thank you for sticking by me through this endeavor.

ACKNOWLEDGMENTS

The author wishes to express sincere appreciation to Drs. Andres Sousa-Poza and Paul Kauffmann, without whom this effort would not have occurred. Additional thanks to Drs. Ralph Rogers and Charles Keating for bringing me to Old Dominion University to pursue this degree and opening the world of academia to me.

I would like to express my genuine gratitude to The US Navy and AMSEC LLC, without their funding and support, this research would not have taken place. In particular I would like to thank Mr. Bob Lidner, Mr. Kevin Alexander, Ms. Noreen Bradshaw, Mr. Chuck Miesch, Mr. Milton Oakley, Mr. Tim Smith, Mr. Henry Villanueva, and Mr. Terry Harper. It has been a great pleasure working with all of you.

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CHAPTER I

INTRODUCTION

Complex Systems

Complex systems such as military aircraft and naval ships are difficult to cost effectively maintain (Economic Report of the President, 2002, US Office of Management and Budget, 2002). One common approach of maintaining these types of complex systems has always been time-directed or preventative maintenance systems. While preventative maintenance under certain conditions can increase reliability, preventative maintenance systems are often costly, increase down time, and allow for maintenance-induced failures, which may decrease the reliability of the system (Ebeling, 1997). In complex systems like naval ships, where the mission completion is of the utmost importance, compelling factors, such as time, cost and little or no room for failure, are sufficient reasons to move toward an effective, knowledge information-based, reliability system.

Many problems are complex, and therefore few are predictable. In this sense, complexity is a question of degree, and specifically the degree of our ignorance (Biggiero, 2001). To view a system as complex, the degree of complexity of the system is based on the quantity of information that is known about that system. The number of elements that make up a system and the large number of interactions among those elements contribute to the existence of complexity. Given that complex systems have the common characteristic of structure

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The journal model used in this dissertation is the Engineering Management Journal

(Biggiero, 2001; Flood and Carson, 1993;), often the researcher will use that characteristic to develop a model of the system.

Vemuri (in Flood and Carson, 1993) alludes to the following four precepts, three of which must be considered based on the measurement, data, theory, law sequence. The fourth precept relates to the criterion that characterizes metasystems:

1. Complex situations are often partly or wholly unobservable, that is measurement is noisy or unachievable (e.g. any attempt may destroy the integrity of the system).
2. It is difficult to establish laws from theory in complex situations as there is often not enough data or the data is unreliable so that only probabilistic laws may be achievable.
3. Complex situations are often soft and incorporate value systems that are abundant, different, and extremely difficult to observe or measure. They may at best be represented using nominal and interval scales.
4. Complex situations are "open" and thus evolve over time.

Given Vemuri's assessment of complexity, models of complex systems can only yield an approximation of the systems' behavior.

Biggiero (2001) has stated that "…"complex" is an object which cannot be predictable because of logical impossibility or because its predictability would require a computational power far beyond any physical feasibility, now and forever." In attempting to model the complex system, "we are seeking to provide a descriptive and explanatory account that provides the simplest, least complex way of accommodating the data that experience (experimentation and observation) has put at our disposal (Rescher, 1998)."

One object of modeling is to transform unclear, poorly articulated perceptions of a system into visible well-defined models useful for many purposes. Models are substitutes for reality, but should be descriptive enough for system elements under consideration to be useful. Principal uses of models have always been to pose "policy" questions to the model and from the results obtained learn how to cope with that subset of the real world being modeled (Sage, 1977).

Three essential steps in constructing a model are:

- determine the problem definition value system and system synthesis elements most relevant to a particular problem
- determine the structural relationship among these elements
- determine parametric coefficients within the determined structure (Sage, 1977).

"The crudest approximation, if it provides hints for the solution of a broad range of problems, has every advantage over the most elegant mathematical law which asserts nothing of interest." – Brewster Ghiselin (in Petrinovich and McGaugh, 1976). Models function as recursive generators of predictions about the system. A model is necessarily simpler than the environment it represents, which allows it to run faster than the processes in the environment (i.e. anticipate the actions). This allows the system to compensate perturbations before they have the opportunity to damage the system (Heylighen, et al, 1995).

Statement of Problem

The approach to model development places an emphasis on the formal reasoning and representation of the system to be studied. The model is formed from the perspective of the individual and the individuals' basic epistemological stance as a basis for the selection criteria. "According to the "modeling view" of knowledge acquisition proposed by Clancy, the modeling activity must establish a correspondence between a knowledge base and two separate subsystems: the agent's behavior (i.e. the problem solving expertise) and its own environment (the problem domain)" (Guarino, 2000). The existing knowledge (base knowledge) forms a framework for the conceptual units by mapping their assumed interrelationships to allow for a more robust study of the system's functionality.

Frequently, large-scale maintenance of complex systems (i.e., a naval vessel) is based on the reduction of the system to its base subcomponents and the use of manufacturer-suggested, time-directed, preventative maintenance, which is augmented during the system's lifecycle with predictive maintenance which assesses the system's ability to perform its mission objectives. This maintenance scheme ignores the complexity of the system it is trying to maintain. By combining the base components or subsystems into a larger system, and introducing human interaction with the system, the complexity of the system creates a unique entity that cannot be completely understood by basing predictability of the system to perform tasks on the reduction of the system to its subcomponents.

Purpose of the Study

This research addresses whether a methodology can be developed that establishes a relationship between the knowledge base tightly held by the system experts, the data captured in the maintenance history of the complex system, and the behavior of the system. The relationship can then be explored as a means to predict failure of the complex system to complete its tasks or missions, thus minimizing system down time for assessment and unnecessary maintenance.

Overview of the Dissertation

In order to explore the feasibility of such a methodology to model complex systems, the dissertation will review the salient literature (Chapter 2) that comprises the bodies of knowledge reflective of the subject matter, specifically: knowledge management, systems modeling and expert elicitation techniques. From the literature we will attempt to derive the need for the methodology in Chapter 3 by showing the 'gap' in the body of existing knowledge that the research is trying to bridge. In Chapter 4 a conceptual model is developed and a plan of research is described to provide an overview of how an existing method of system behavior modeling – failure mode and effects analysis (FMEA) – may be modified to provide a more holistic view of legacy system behavior through the use of expert knowledge. The methodology presented allows for a transfer of tacit knowledge into an explicit form to make predictions regarding the system behavior. Results from the application of the conceptual methodology are presented (Chapter 5) and discussed (Chapter 6) providing suggestions (Chapter 7) for further research.

CHAPTER II

LITERATURE REVIEW

Overview

For this research, the significant bodies of knowledge permeate systems management, knowledge management and systems modeling. This research effort integrates these to develop a systems methodology to provide organizational support to the management of a complex maintenance system.

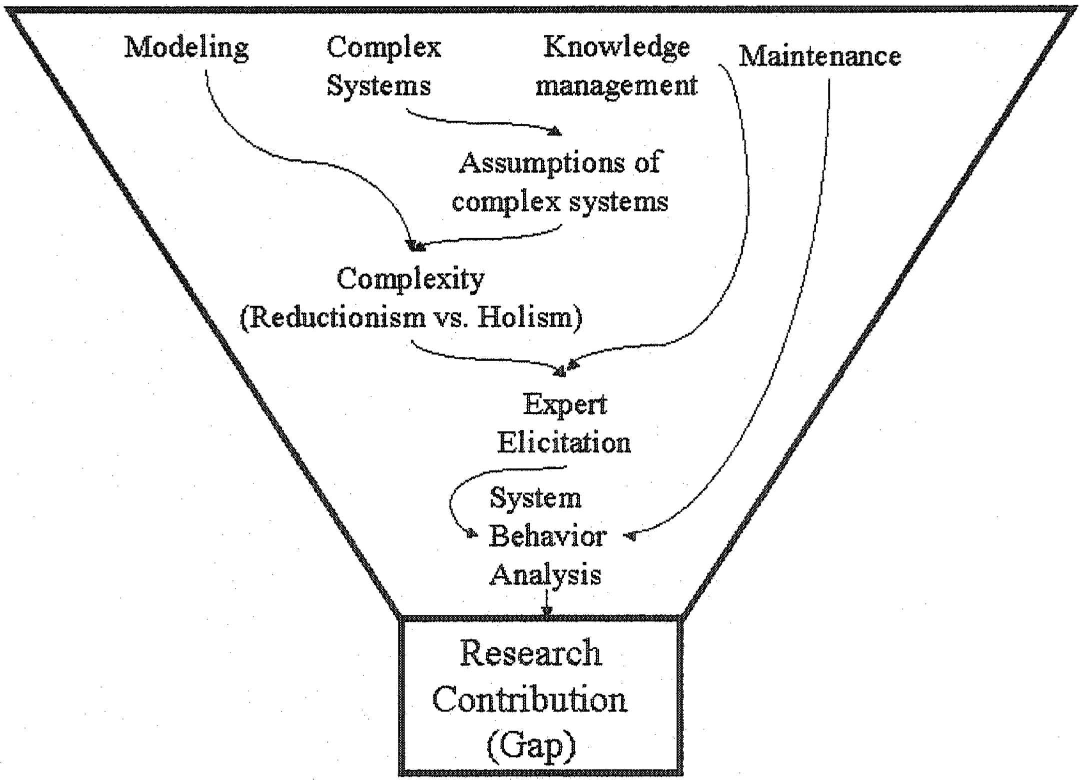


Figure 1 Funneled Representation to Gap in the Literature.

Figure 1 takes the perspective of the literature to be a wide funnel of knowledge that can be gradually narrowed until we reach that 'gap' in the body of knowledge where the research attempts to explain the gap through the development of a methodology. By development of the methodology, the gap is then closed, thus contributing to the broadening of the body of knowledge. This chapter will present the literature to promote the foundation for the methodology presented in the next chapter.

Systems Modeling

According to Sage (1997), a major objective in the management of such a system is to obtain information necessary to organize and direct individual programs associated with the production of products and services. He further states that this information can only be obtained through an appropriate program of systematic measurements and the development of appropriate models for use in processing this information. In effect, to appropriately manage a large complex system, it is necessary to develop a decision support system to aid in the decision making process.

As with all decision support systems, the "twin engines" are data and models. Models provide the means for the conversion of data into actionable information. In fact, the model pinpoints the actual data needs. By the same token, the model itself is constrained by the available data (Mohan and Holstein, 1999). Model development is further compounded if the system under observation is complex. The rendering of this information into useful and meaningful data requires the development of an appropriate model. In general, models – simplification of "real world" processes by making assumptions concerning the system's true state of nature – have uncertainties due to incomplete knowledge. These uncertainties arise when the particular value or population of values of concern cannot be presented with complete confidence because of A lack of understanding or limitation of knowledge (Haimes, 1998). This usually tends to cause a dilemma for managers trying to make decisions, due to lack of supportive measures available that accurately model system behavior due to the complexity of the system. Managers are then left to rely on the knowledge of the "system experts" who routinely work with the system and base their judgments solely on their advice.

The decision support system must include a flexible base methodology to allow deployment across various system classes. The conflict of viewpoints involved in producing the precise form of the methodology to be deployed is in itself problematic (Flood and Carson, 1993), as there are a vast number of stakeholders with individual needs that must be addressed. While basic similarities will exist across comparable systems, the variations of equipment within specific system classes and varying skill level of the system operators in maintaining and operating the system(s) give pause to deployment of a single knowledge-based decision model. The model must have flexibility for deployment across the various platforms. Consequently, the methodology of the system design must also be flexible so that implementation of the system is consistent across the platforms, but still is specific for the individual system class. This leads to the differentiation of the various types of system methodologies that may be used for the development of the decision support system that is the ultimate goal of this research endeavor.

Assumptions of Complex System Principles

As previously stated, the proposed research model addresses the management of a complex maintenance system. With the idea of a "complex" system in mind, it becomes important to clarify the notion of what constitutes a complex system. While various methodologies exist for the development of system-based initiatives, each methodology must adhere to a basic underlying group of principles to ensure that an effective study and an understanding of the system, in its current state, is achieved. The specific approaches may differ but the underlying 'logic' is a common thread running through each of the methodologies (Keating, 2000). The following four system tenets amalgamate the concept of complex system analysis.

- Simple vs. Complex Systems
    - Characteristics of a complex systems (Jackson in Keating et al, 2002)
        - Large number of variables or elements
        - Rich interactions among elements
        - Difficulty in identification of attributes and emergent properties
        - Loosely organized (structured) interaction among elements
        - Probabilistic, as opposed to deterministic, behavior in the system
        - System evolution and emergence over time
        - Purposeful pursuit of multiple goals by system entities or subsystems (pluralistic)
        - Possibility of behavioral influence or intervention in the system
        - Largely open to the transport of energy, information, or resources from/to across the system boundary to the environment
    - Characteristics of a simple system
        - Small number of variables or elements
        - Poor interactions between elements
        - Ease of identification of attributes
        - Deterministic behavior in the system
        - System does not evolve over time
        - System is not effected by behavioral influences
        - Largely closed to the transport of energy, information, or resources from/to across the system boundary to the environment

- Self-Organization. Self-organization holds that most of the structural and behavioral properties of a system emerge through interaction of the system elements (Clemson, 1984). Therefore, the actual design of a system can only be partially specified in advance of system operation. From the systems perspective, this explains why the most thoughtful and carefully designed systems have unintended consequences. In essence, system behavior and informal structure emerge only through system operation, regardless of the detailed design efforts conducted prior to system deployment.

> *Effective design of complex systems ensures that only the essential constraints are imposed on the operation of the system. In systems theory this concept is known as minimum critical specification (Cherns). Over-specification of system requirements is: (1) wasteful of scarce resources necessary to monitor and control system performance, (2) reduces system autonomy which in turn restricts the agility and responsiveness of the system to compensate for environmental shifts, and (3) fails to permit subsystem elements to self-organize based on their contextual knowledge, understanding, and proximity to the operating environment. Therefore, self-organization suggests that system solutions should specify only the minimal requirements necessary to achieve system objectives. (Keating, 2000)*

- System Darkness. This concept suggests that the complex system when viewed from any vantage point will not clearly present itself in its entirety. The complex system and any representation of the complex system can only be described by what is known, observed or suspected. Unknown, unobserved, unrepresentative, and emergent characteristics will be present and not known to the systems architect.

- Complementarity. The principle of complementarity suggests "Any two different perspectives (or models) about a system will reveal truths about that system that are neither entirely independent nor entirely compatible" (Clemson, 1984). Each system perspective is correct from a particular vantage point of the system. In

> addition, each system perspective may also be considered, to some degree, incorrect from an alternate system vantage point. The important argument is that there are multiple system vantage points, each adding to a more holistic impression of the system. Shifts in vantage points, environmental conditions, or knowledge will influence perspectives of a system. It is naive to consider there is only one system perspective that is "correct". Therefore, it is a mistake to conduct inquiry as to which system perspective is 'right'. Assumption of a 'right' system encourages advocacy and competition instead of dialog and collaboration. (Keating, 2000)

Additionally, a system study must also address the needs of the individual(s) who express interest or concern for the performance of the system to meet a desired outcome or functionality of the system under study. To accomplish this task, a set of criteria needs to be established to determine whether the system architect has developed a level of competency in understanding the system under study, and has determined an effective method of addressing the concerns of the desired outcomes of the system. The use of the developed criteria can then be used to evaluate the study (design, approach, accomplishment, effectiveness, strengths, weaknesses, etc.).

According to Jenkins (in Flood and Carson, 1993), in order to properly frame the problem context, the systems architect must be able to answer the following questions. How did the problem arise? Who are the people that believe it to be a problem? Who made the decision to implement a planning decision and what is the chain of argument leading to making a decision? Is the problem the right one and is the solution important? While these statements are part of the first phase of the Jenkins model, they remain true and pertinent in all attempts at the study of any system, simple or complex. These questions should lead the systems architect to the following statements and conclusions to begin his study of the system.

- What are the objectives of the system as defined by the entity identifying the problem? How are these objectives being expressed?
- Development of critical system issues (Relevant Circumstances)
    - What are the primary objectives of the stakeholders that the system analysis is attempting to resolve?
- Assumptions and constraints for system and study (Rationality)
    - What assumptions must the systems architect make to begin his analysis? Are there any constraints (time, budget, data) that the systems architect must work within?
- System problem statement
    - A concise, descriptive statement of the problem; developed to be a representation of the best 'current' framing of the problematic situation.

The biggest problem that a systems architect faces is in the selection of the methodology he will use to analyze the system. In order to effectively select the methodology, he must have a clear picture of the system and how it functions in order to select the methodology(ies) that best fit the situation at hand. The systems architect should begin by addressing the what (system), how (sub-systems) and why (the wider-system or system environment) of the problem context (Checkland, 1999). The problem context developed is meant to give the systems architect a means to clearly identify the system that is to be studied. That is to say that the problem context should give the systems architect the ability to identify the system whose output/outcomes are the ones perceived to be the problem. He accomplishes this by performing the following tasks:

- Define the System. What is the system to be studied? Is it the correct system? From what perspective is the system to be viewed? What components make up the system?
- Bounding the System. What are the system boundaries? While the initial boundaries may be arbitrary, the systems analyst must make reasonable assumptions as to what those boundaries should be.
- System representation. How is the system to be represented? How are the systems components (subsystems) interactions presented to show the relations of the system with its environment, the relations within the system among the subsystems, and its inputs and outputs of the system?
- System output/outcome (Actual vs. Ideal). What/how is the system currently functioning vs. how would the system stakeholders like for the system to function. Requires the architect to establish the needs of the stakeholders and the capabilities of the current system.
- System expectations. What are the stakeholders' expectations for the system? How do they envision the system to function?
- System measure of performance. How is the system's (under study) performance measured? Is the measurement to be quantitative or qualitative? Who is measuring the system performance?

Another perspective on modeling system behavior worth looking at was developed by Gibson. Gibson's methodology (Gibson, 1991) consists of six major "steps"

- Determine system goals
- Establish Alternative ranking criteria
- Develop alternative systems solutions

- Screen and rank alternatives
- Iterate
- Action and deployment

While a stepwise systems analysis is not appropriate in most cases, the spirit of Gibson is that these "steps" should serve as a guide to developing a complete and useful analysis.

In the first step of Gibson's methodology, goal development, Gibson recommends the following seven steps:

- Generalize the question – Here, the systems analyst ileaves enough room to reframe the problem after knowledge is gained through the iterative process.
- Develop a descriptive scenario – this is the development of the system view. It assumes that the same view is held by all and aid in the representation of the system
- Develop a normative scenario – this establishes a minimum set of constraints by questioning whether constraints are necessary
- Axiological component – Because the explicit cannot exist at a tacit level, a developed solution in a particular context may not be transferable to a different group with a different view of the problem due to differing values and beliefs.
- Objectives tree – a graphical display of the goals of the system. It is used to critique the organizational hierarchy of the goals. Tree branches are additive to indicate how higher-level goals may be achieved through the support provided by accomplishing objectives.
- Validate – Through each step of the goal development process, the system analyst tries to validate and consolidate his findings. He is ultimately asking, "Is the problem properly framed?"

- Iterate – go through the process again.

It is interesting to note that Gibson's first step in accomplishing system analysis attempts to mirror the ideology that a problem context should be developed. However, this is problematic with the idea put forth in this paper, that the problem context should determine the methodology to be used for the system analysis. As stated earlier, a complex system has emergent properties that are not clearly defined due the concept of "system darkness". Gibson's approach is rather prescriptive, lacking flexibility in this process with the assumption that all stakeholders will share the same systems view. This prevents the development of a thorough understanding of the system, as when the system is viewed from multiple perspectives and as those perspectives merge, there is a better understanding of the problem situation and, therefore, the system problem becomes more contextually bounded by those views.

Gibson's next step in performing a systems analysis is to provide an alternative ranking criteria based on an index of performance. Accordingly Gibson has provided his 'ideal' characteristics of that index:

Index of Performance

- Measurable
- Objective
- Non-relativistic
- Meaningful
- Understandable

The unanswered question relating to Gibson's index of performance characteristics is to what purpose? The use of these performance metrics is too limiting to achieve the intent of the ranking of alternatives. They lack a means to identify a systematic way of measuring the suitability for the alternatives – a standard. The index of performance, as put forth by Gibson, provides minimal structure for the decision process and is biased to the value and belief system of the stakeholders and the systems analyst.

In developing the alternative system solutions, Gibson provides little structure for the process. Instead of the structured approach, as with his stepwise methodology, he encourages the systems architect to be creative. The basis for this unstructured approach is apparent in the built in control the stepwise methodology purports, that the ranking, based on the performance indices will 'screen' unlikely or unviable alternatives.

The process of iteration, in the Gibson methodology, provides focus for the system analysis. It allows for 'fine tuning' of the analysis process. Models function as recursive generators of predictions about the system. A model is necessarily simpler than the environment that it represents, and this allows for it to run faster than, i.e. anticipate the actions, the processes in the environment. This allows the system to compensate perturbations before they have the opportunity to damage the system (Heylighen, et al, 1995). In much the same way, Gibson's process of iteration allows for the analyst to reduce the alternatives to a manageable number with the added benefit of the 'buy-in' of those interested parties involved with the process.

The final step in Gibson's methodology is the action and deployment of the solution(s).

Gibson makes a great contribution the body of system methodologies. He has provided a structured approach that organizes the problem, recognizes the problem's context, has consideration for the values and beliefs (axiological component) of the interested parties, is iterative, and takes an intelligent approach to problem solving. However, caution should be used in the application of this methodology, as with others, the system, the context of the problem, and the environment that houses both should determine the use of a particular methodology. No one methodology is better than any other when it comes to system analysis. It is a matter of "fit" between the contextually rich interrelationships of the system, the problem context and the methodology. A big mistake that systems architects are prone to make is to follow a stepwise progression through a particular methodology because they are comfortable with it. The system and problem context must "choose" the methodology, not the other way around.

- Methodology selection. What is the methodology(ies) that best fit the situation? How was that determined and by who?
- Application of the methodology. Was the methodology(ies) selected properly applied in the analysis of the system?
- Development of a systems model. The model should be an abstract of the system under study. To what level of detail was the model developed?
- Goodness of Fit. By "goodness of fit" we try to identify the rich contextual relationships between the methodology used by the systems architect to study the system and the problems identified by the problem context. This attempt should be satisfying. Does the methodology used fit the problem and the system as developed in the problem context and the system model?
- Representation effectiveness. Does the model effectively and efficiently depict the system and the complex interrelationships of the system (interaction of system with its environment, interaction of the subsystems)? Does the model identify gaps in our knowledge of the system?

- Limitations and assumptions for system representation. What are the assumptions and limitations of the model? What does/does not the model express?

Complex System Model Development

Each individual's ontological view of the world tends to bias the perspective from which they would observe the system. The level from which the observer views the system (Checkland, 1999) lays the foundation from which the researcher, as an observer, bases his assumptions. The researcher's viewpoint is predisposed due to the worldview he posses. While basic truths may exist in the system as a whole, the viewpoint of the observer is based on knowledge that the observer has gained throughout his entire existence. He has developed a knowledge basis from which he has tried to adapt to the given situation, which has resulted in the formation of his viewpoint of the situation. That is to say that the system exists on many levels, but the view from which it is to be observed, and the model developed, is dependent solely on the observer.

This implies that the oversimplification of a model results from a lack of knowledge on the part of the observer. From a systems analysis viewpoint, simplification is not necessarily a bad thing.

> *It clearly makes eminent sense to move onwards from the simplest (least complex) available solution to introduce further complexities when and as – but only when and as – they are forced upon us. Simpler (more systematic) answers are easily more codified, taught, learned, used, investigated, and so on. The regulative principles of convenience and economy in learning and inquiry suffice to provide a rational basis for systematicity- preference. Our preference for simplicity, uniformity, and systematicity in general, is now not a matter of a substantive theory regarding the nature of the world, but one of a search strategy – of cognitive methodology. In sum we opt for simplicity (and systematicity in general) in inquiry not because it is truth-indicative, but because teleologically more effective in conducing to the efficient realization of the goals of inquiry. We look for the dropped coin in the lightest spots nearby, not because this is – in the circumstances – the most probable location but because it represents the most sensible strategy of search: if it is not there, then we just cannot find it at all (Rescher, 1998)*

In general, the simple model is a manifestation of what the researcher presumes to know, his base approximation of the system. While this concept at first seems a little clouded, an interpretation of this concept is as follows: From the perspective that the system is viewed (ontologically), a model is developed. There must be a base level of knowledge about the system to effectively engage in a systems-based initiative, which results in the development of the initial framework of the interrelations of the system's conceptual units (Checkland, 1999). Through trial and error, the researcher gradually adjusts the model (problem solving expertise), with each iteration, in an attempt to achieve a bridging of the gap between the ideal outcomes of the system and the actual outcomes of the system (gap – the problem domain). With each iteration, knowledge is gained (epistemological part) as to the assumptions the researcher had to make as he adjusted the model. The iterations themselves revealed to the researcher as to whether his initial assumptions of the unit's interrelations were true or false. Progressing through the iterative process, the researcher is learning about the system and gaining knowledge that did not previously exist. As the researcher gains knowledge during this process, it will become evident to the researcher that the model must then be reoriented to reflect the new knowledge. The result is a more mature level of systems knowledge compared to the base knowledge the researcher began with. This mature knowledge will lead to a greater understanding of the actual system under study and more effective insight/resolution to the disparity of the ideal and actual system outcomes (gap closure).

Assuming that the model of the system is a dynamic model, based on an iterative modeling process, and given the ontological and epistemological view of a researcher attempting to model a system for study, the following four points (as derived from the literature) are proposed as a counter argument to the effects of oversimplification of a model.

Point 1. *There is no perfect "true" model of any system. For a given system several models may exist (from an ontologically materialistic view) that may be adequate for solving the problem situation faced by the researcher.*

Any systems model developed is based solely on the viewpoint of the observer (Checkland, 1999). The observer's base knowledge of the system establishes the functional utility for the framework of the system component relations in achieving systems goals (outcomes). As in the 'black box' theory, numerous independent observers who are at consensus with the inputs view the system and outputs of the system, yet are in disagreement about the transformation processes that occur within the system. As the researcher gains knowledge of the diverse communications and actions of the units that comprise the system, an approximation of the true nature of the system is developed, but is only an approximation. With multiple observers, many diverse approximations will be developed; most will be quite different based only the observers ontological view.

Point 2. *Acceptance of the knowledge gained by the researcher will tend to be rejected if it is inconsistent with the bulk of knowledge possessed (base knowledge) prior to system study.*

If an individual(s) or group(s) evaluates a system model modified by a researcher after multiple iterations, without the individual(s) or group(s) having the maturity in knowledge the researcher has gained through the iterative process, a dysfunctional dynamic will exist between the researcher and that individual/group (Gibson, 1991). The individual/group lacks the ability to effectively evaluate the model because it does not comprehend the system at the same knowledge level the researcher is presenting in the "iterative" based model. In order for the model to become acceptable, the individual/group must be brought up to the knowledge level of the researcher through other means, else the knowledge gained by the researcher will be lost on the individual/group expressing interest in the system of study.

Point 3. *A systems based methodology is chosen to fit the ontological and epistemological view of the researchers "best fit" model. How the researcher views the system is fundamental in determining his approach to "problem solving".*

The model is only a conceptual representation of the researcher's approximation of the system. Does the model effectively and efficiently depict the system and the complex interrelationships of the system (interaction of system with its environment, interaction of the subsystems)? Does the model identify gaps in our knowledge of the system? While these questions come to mind when thinking about the model, the methodology must fit the problem context (Guarino, 1995). In relation to the model, problem context is the perception of the researcher of the gap between the ideal outcomes of the system and the actual outcomes of the system. Again, the context (like the model developed) is a function of the ontological view and base knowledge of the researcher.

Point 4. *Models are not static representations of the system being studied. Models will change as knowledge is gained.*

The model is an entity and representation of the system under study. It is not the system itself. The framework (base knowledge) and conceptual units of the system created by the researcher are an attempt to examine and explain system behavior (Checkland, 1999). As the iterations of the study progress, further knowledge is gained and the initial framework and conceptual units must be altered to reflect this (Gibson, 1991).

It is most important to note that the results of a systems study are highly subjective and duly apt to interpretation to those individuals who read them. A system study is intended for the use of the individual(s) (or stakeholders) who perceive a problem with the actual outcomes of the system as it was currently operating based on their individual perspective. The individual is naturally biased in his/her perspective based on his/her own ontological stance. Even in the reading of the study, the interpretations and use of the presented work is highly subjective and innately dependent on the ontological and epistemological views of the reader (Cocchiarella, 1996). As stated previously, acceptance will be based on knowledge individuals already posses.

Morgan introduced five approaches to lessen a similar paradox in the determination of research dilemmas faced in management science (in Gill and Johnson, 1991). While the underlying concepts are true in systems science, the concepts have modified here to more appropriately correspond with systems science. The researcher should ask the following questions about his analysis.

1. What was the intended use of the body of work produced by the researcher? Is the work relevant to the problem?
2. What were the objectives of the stakeholders? Were these objectives addressed in the study?
3. What was the researcher trying to gain from the study of the system? Did the study produce a work that is usable by others to obtain their goals?
4. Were the limitations, assumptions, and judgments made by the researcher consistent with the perspectives of the stakeholders?

5. Did the researcher "look outside the box" of a particular methodology to determine the best approach to the situation?

By attempting to keep those questions mindful, the researcher will address the concerns of the interpretation and use of his work when applied to the system studied.

Reductionism vs. Holism

The concepts of modeling and complex systems are then combined to form the arguments for reductionism and holism as presented in figure 1. Systems, Cybernetics, and Complexity all share an orientation towards the study of organization of phenomena in taking a "big picture" perspective (Kuhn, 2002). From a holistic view, the system is observed in its entirety to study 'complexes of information and meaning' such as patterns, configurations, processes, and types. From a reductionistic view, an attempt is made to decompose complex activities and localize the components within the complex system to provide a foundation for dynamical analysis (Bechtel, 2001). These diametrically opposed views have been characterized (Ragin, 1989; Verschuren, 2001) as the (holistic) case study as 'case-oriented', in contrast to a (reductionistic) 'variable-oriented' approach. Often in research we can also describe them, respectively, as qualitative and quantitative. Both theoretical frameworks share a base in scientifically derived knowledge, an interest in understanding non-living (artificial/machine) and 'living systems', and a belief that to more properly understand phenomena, a larger, more inclusive view is necessary. Van Gelder (in Bechtel, 2001), for example, identifies homuncularity, the idea that one can analyze systems into components, as allied with such notions as representation, computation, and sequential and cyclic operation, all of which he views as incompatible with and supplanted by a dynamical approach. Efforts to decompose and localize processes are often ridiculed [by holist] as reductionistic and conceived of as unable to explain the operation of complex systems. Recognizing that phenomena can be more properly understood as parts of systems also implies that the observer has the ability to delineate with some security the proper systems and/or components of systems implicated when investigating any specific phenomena (Kuhn, 2002).

As engineers, scientist and researchers, decomposition of a complex system into its subsystems and elements for model development is an attempt to isolate variables that uniquely determine the state of the complex system under study. The reductionist has to make the assumption that the holistic view of the system that he has chosen to decompose is accurate and that the variables that uniquely determine its state are known. In principle, the application of such a theory to real problems requires the simultaneous measurement of all these variables. This is rarely feasible in practice, where often we will not even know what the important variables are. All that we may be able to achieve is to make a sequence of repeated measurements of one or more observables. The relationship between such observations and the state of the system is often uncertain. It is therefore unclear how much information about the behavior of the system we can deduce from such measurements (Stark, 2000).

In the true metaphysical application of reductionism, as characterized in the philosophical literature, it may in fact be difficult to express the operation of a complex system once it is decomposed into its components, but from the ontological perspective of a systems engineer there is logic in the decomposition of a large complex system. Reduction of a system into its base parts allows the researcher to achieve two goals, one being quantification the other being able to establish researcher independence (Verschuren, 2001).

Quantification allows for the establishment of a metric means for measurement. This measurement allows for comparison of the results of the research, as well as replication and control of what the researcher has accomplished. Additionally, quantification allows for the counting of observation units having certain characteristics thus allowing for multi-variate data analysis. Finally, the belief that quantitative research is more valid than qualitative research, due to its subjectivity, lends to the widespread use of quantitative research (Verschuren, 2001).

Moreover, a reductionistic type of data gathering may help achieve researcher-independent results (Verschuren, 2001). This would allow for systematic observation and quantitative content analysis, rather than for participant observation and open-ended qualitative content analysis. A final argument for reductionism is that the differentiation between research units and observation units may act as a kind of cross-validation.

> *As most hypotheses come into being inductively as an overall impression of the researcher, testing them in an inductive way ceteris paribus is weaker than doing this reductionistically. For instance, imagine a researcher formulates the hypothesis that of two groups the members within group 1 interact significantly more than those of group 2. Then looking at all dyads in each group, counting the number and duration of interactions per dyad within a certain period and summating over all dyads and periods, for most people will be more convincing as a test of the hypothesis, than an overall impression of a researcher who observes these groups as wholes. This confidence is based in large part on the fact that the researcher often has a number of ideas and implicit assumptions as to the object of research. By looking at its elementary parts (i.e., observation units) instead of at the object as a whole, a professional researcher will 'forget' these assumptions and ideas for the simple reason that these do not directly regard the individual parts (Verschuren, 2001).*

While reductionism on the surface appears to be a most valid means to approach to isolate the variables necessary to understand a complex system, there are some limitations to the reductionistic approach in building a model of a complex system. There is a familiar idea that the whole is more than the sum of its parts. Petrinovich (1976) points to the major difficulty with reductionism stemming from two sources: (1) it distorts the structure of natural events, and (2) it embodies a misleading conception of the meaning of individual differences. The first point refers to the fact that to use techniques such as analysis of variance one must select a range of stimulus values in some arbitrary fashion, must choose a dependent variable to measure that is arbitrary, and often limiting operational translation of the conceptual variables in which the in which the experimenter is interested and must abstract the entire experimental operation out of a complex of variables in which the behavior is embedded.

By separating the variables controlling the behavior from the fabric from which they are embedded, the pattern of correlations between variables as they exist in nature is destroyed. Context dependencies, interconnectedness, and functionality are lost. "Because a cause was taken to be sufficient for its effect, nothing was required to explain the effect other than the cause." (close parenthesis here?) Consequently, the quest for causes was environment free. It employed what is now called 'closed-system' thinking' (Ackhoff in Kuhn, 2001). In establishing the viability of research surrounding the development of the deconstruct subsystem model, acceptance of the principle of determinism is required. This principle implies that general laws exist which allows for the complete predictability of behavior if measurement is precise and if all relevant variables could be controlled. It also implies that the system had been deconstructed such that the subsystem under observation is no longer complex and completely understood.

Verschuren (2001) clarifies the second difficulty with reductionism, "In general not the sum of individual parts of a system makes up an equilibrium, but the integrated whole of a system." His statement alludes to the concept that without the holistic view, there is not a way to determine how perturbations to the deconstruct subsystem model will effect the behavior of the complex system. This suggests that the knowledge gained by isolating the subsystem for study may not have a significant use in understanding the complex system's response (macro) to the stimulus introduced at the subsystem level (micro).

In order to reconcile the problem of not being fully able to predict the behavior of a complex system through the development of complete models with full predictive capability though either holistic or reductionistic reasoning, the following assertions are put forth:

1. While important to establish a base knowledge level when studying a complex system, system models do not represent the system but serve as an approximation of the system and current knowledge base of the researcher.
2. Models of complex systems require an iterative development process to allow for variability inherent in complex systems and modifications due to the researcher's knowledge.
3. Statistical and other quantification methods, used in conjunction with reductionism to evaluate the behavior of the subsystem, may not yield the same results when applied at the system level.
4. Reductionism should be used in conjunction with holism to identify those variables in the system, which control "meaningful proportions" of the total variance in behavior of the complex system.
5. Predictions made from the use of complex models will be probabilistic at best.

Knowledge Management

Whereas data is directly observable and measurable, knowledge is a statement about a hypothesis. The process of knowledge management is a means to develop the specification of a meaningful likelihood function based on the notion of probability (Singpurwalla, 2003) that is useful to others experiencing similar queries into the state of the hypothesis at varying degrees. The combination of knowledge with related data creates information that may be used to support or reject the hypotheses that are generated. Von Hoffman (1999) defines knowledge management as a formal process of figuring out what information a company has that could benefit others with in the company, then devising ways of making it easily available. As knowledge is an important strategic asset for organizations that leads to improved organizational performance, so it reasons that knowledge management must be concerned with many processes aimed at designing and managing these process as effectively as possible.

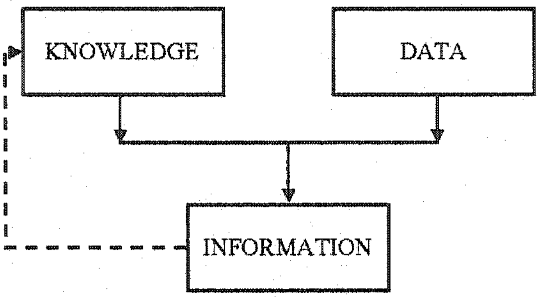


Figure 2, Relation of Knowledge to Data and Information.

While this idea sounds simplistic at first, it is necessary to discuss the two distinct but very different dimensions of knowledge that have a profound impact on the ability of an organization to capture that knowledge and make it available – tacit and explicit knowledge (Polanyi, 1967). One dimension emphasizes the capability to help create, store, share, and use an organization's explicitly documented knowledge. Explicit knowledge is very formal and systematic, it can be easily communicated and shared, in product specifications, in scientific formula or a computer program (Nonaka, 1991). As such, science and engineering are forms of organized [explicit] knowledge – a collection of hypotheses in some logical manner (Singpurwalla, 2003). Often explicit knowledge is readily available to all within the organization. The strategy for this dimension emphasizes codifying and storing knowledge. Typically, knowledge can be codified via information technology (Lee & Kim, 2001; Swan, Newell, and Robertson, 2000). Codified knowledge is more likely to be reused. The emphasis is on completely specified sets of rules about what to do under every possible set of circumstances (Bohn, 1994). Then management of explicit knowledge is similar to the modern library system, in that the organizations explicit knowledge is collected, stored and made readily available to those who need to access it. The true need for knowledge management arises from the need for use of the second type of knowledge that exists –tacit knowledge.

Tacit knowledge is highly personable and it is hard to formalize and communicate (Nonaka and Takeuchi, 1995). Michael Polanyi (1967) expresses the concept well: "We can know more than we can tell." As such, tacit knowledge is deeply rooted in an individual's commitment to a specific context – a craft or profession, a particular technology or product market, or specific activities of a work group or team. Tacit knowledge falls within the realm of an individual's holistic perspective as it relates to the cognitive dimension that the expert seemingly takes for granted, and therefore cannot easily articulate them. As per this dimension, the strategy uses dialogue through social networks including occupational groups and teams (Swan et al., 2000). It helps share knowledge through person-to-person contacts (Hansen et al., 1999). This strategy attempts to acquire internal and opportunistic knowledge and share it informally (Jordan & Jones, 1997). The existence of tacit knowledge for use in knowledge management however, gives the foundation for the development of explicit knowledge based on tacit knowledge: Knowledge can be obtained from experienced and skilled people.

In its purest context, knowledge management is much more than the generation of a contextual database of knowledge that is gathered by an organization and stored for later use. It involves the exploration of the four distinct patterns of knowledge creation and exploits them enabling organization to further its objectives (Polanyi, 1967; Nonaka, 1991; Choi and Lee, 2002).

Tacit to Tacit (Socialization)	An individual shares tacit knowledge with another. For example, an apprentice learns form a master through observation, imitation and practice. Skills learned become part of the individual's tacit knowledge base, becoming 'socialized' into the craft being learned. In such a fashion, it is a limited form of knowledge creation because as in the example the master and apprentice never gain insight into the craft knowledge. Because the knowledge never becomes explicit, it cannot be shared by the organization as a whole.
Explicit to Explicit (Combination)	Because the knowledge is explicit, it can readily be disseminated through the organization. The knowledge can then be combined with other explicit or tacit knowledge creating new knowledge that the individual may use. While new knowledge may be created in this form, this combination does not really extend the organizations knowledge base.
Tacit to Explicit (Externalization)	The process of articulation (converting tacit knowledge to explicit knowledge) allows for the sharing of tacit knowledge throughout the organization
Explicit to Tacit (Internalization)	As a result of new knowledge, a better cross-section if individuals within the organization may begin to internalize explicit knowledge allowing them to broaden, extend and reframe their individual tacit knowledge.

Table 1, Knowledge Creation Patterns, adapted from Nonaka, 1991.

The problem for knowledge management then becomes how to articulate the tacit knowledge to a more useful explicit form for dissemination to the organization.

Expert Knowledge Elicitation

Since a great deal of knowledge is tacit, one way to To model the system, the concept of reductionism is key to reducing the system to its base components. However, to understand the rich interactions of the system, to minimize the effects of "system darkness" that is limiting the overall context in which the system is operating, understand the ability of the system to compensate for the various perturbations resulting from the system subcomponents failures and determine the human capability to repair or realign the system to minimize their effects, a holistic perspective must also be deployed. One way to develop a holistic perspective is to capture the [tacit] knowledge held by various experts on the system and integrate that knowledge into the system model (Rush and Wallace, 1997; Baecher, 2002; Checkland, 1999; Gibson, 1991).

The key to any knowledge-based system is the integrity of the process, which elicits and represents the human expertise on which the system is based (Rush and Wallace, 1997).

Baecher (2002) defines the quantification of expert opinion in the form of judgmental probabilities as expert elicitation. The process of knowledge elicitation (Rush and Wallace, 1997) must define two essential items:

1. The core concepts or components of the decision situation, and
2. The manner in which these components interact with each other.

The literature suggests that there are a variety of knowledge elicitation techniques that may be used for this purpose as detailed in table 2.

Technique	Description	Reference
Brainstorming	Encourages idea generation; expands approach through creativity	Moore, 1987 Van Gundy, 1988
Delphi Method	Structured sharing for gaining group consensus; useful for assimilating knowledge/opinions	Linstone and Turnoff, 1975 Roth and Wood, 1990
Consensus Decision Making	Uses consensual group dynamics to enhance the knowledge acquisition process	McGraw and Harbison-Briggs, 1989 Van Gundy, 1988
Nominal Group Technique	Organizes experts as nominal group functioning independently (structured approach to brainstorming)	Frank, 1982 Huseman, 1973
Protocol Analysis	AKA Think Aloud, participants are taught to think aloud as they solve a problem, provides rich description of the individual's analytical process	Newell and Simon, 1972 Ericsson and Simon, 1984
Reclassification/Goal Decomposition	Participant describes goals or outcomes. Works with an analyst to define the events evidence or scenarios that would support the desired outcome.	Cordingley, 1989

Table 2, Knowledge Elicitation Techniques, adapted from Medsker, et al (1995) and Hoffmann et al (1995).

Protocol Analysis (Newell and Simon, 1972 and Ericsson and Simon, 1984) and Reclassification/Goal Decomposition (Cordingley, 1989) require each expert to work independently and closely with the researcher. There is evidence, however, that supports the use of multiple experts to reduce the bias resulting from the beliefs of an individual. Lock (1987) notes that consensus distribution formed by combining the qualified degrees of beliefs by experts is shown to frequently out perform individual experts in forecasting. Specific examples of consensus methods include brainstorming, nominal group technique, and the Delphi Method. Accordingly, Turban and Tan (1993) note the following benefits of using multiple experts.

1. On the average, a group will make fewer mistakes than single experts
2. Several experts in the group can often reduce, or eliminate the need for a world class expert
3. The collective expertise of multiple experts will often be broader and deeper than that of a single expert.
4. Often the simultaneous consideration of the experts' thoughts will result in deeper insight into the problem at hand.

The group may serve to enhance individual commitment, help with resolving ambiguous and conflicting knowledge, and facilitate creativity along with watchfulness for errors.

The underlying theme of the literature suggest as supported by Baecher (2002) is that a successful process for eliciting expert judgment must include the following steps:

1. Decide on the general uncertainties of the probabilities of which need to be assessed.
2. Select a panel of experts displaying a balanced spectrum of expertise about the unidentified uncertainties.
3. Refine issues in discussions with the panel, and decide on the specific uncertainties the probabilities of which need to be assessed.

4. Expose the experts to a short training program on concepts, objectives, and methods of elicitation judgmental probability, and on common errors that people make when trying to quantify probability.
5. Elicit the judgmental probabilities of individual experts on issues pertinent to heir individual expertise
6. Allow the group of experts to interact, supported by a facilitator, to explore hypotheses, points of view, and quantified estimates of probability, toward the goal of aggregating probabilities and resolving the breadth of opinion.
7. Document the specific process used to elicit judgmental probabilities and communicate the results back to the panel of experts.

Structured Approach to System Behavior Analysis

In order to determine the general probabilities of the system behaviors to be addressed, it also becomes apparent that there is a need to develop a structured approach to the elicitation of the knowledge. Again, the literature suggests a variety of methods that may be incorporated to focus the experts in a manner that will structure the process to provide the necessary focus while allowing the expert to view the system in a broad holistic manner. This provides a structure to the decomposition or reduction of the complex system for analysis of the anticipated or possible system perturbations that may occur. [Table 3]

In effect, a structured behavior analysis approach when applied to the system, supplies a framework for the representation of the data rather than the data collection. This abstract framework (Cooke, 1994) assumes particular types of structures or components (e.g. Actions, functions, rules) as well as their relationships to one anther (e.g. hierarchical). While many of the techniques are highly graphic (e.g. time line analysis, fault trees, diagram drawing) they enable illustration and make more vivid relationships among the elements in the system

(Miester, 1985) and the interaction of the personnel in contact with the system. Another form of structure that is also used is the Failure Modes and Effects Analysis (FMEA). Like the highly graphic techniques discussed, the FMEA establishes a hierarchical structure for the behavior of the system in response to failure of subsystems and components. It is suggested in the literature (Cooke, 1994, McGraw and Harbison-Briggs, 1989) that use of these types of structural techniques may be used to handle multiple experts in that the relatedness estimates that are used as input can be aggregated over a number of experts to generate a composite structural representation of the system and its behavior in response to stimuli.

Technique	**Description**	**References**
Time Line Analysis	The analyst determines time critical sequences of tasks using the informant's definition of the temporal relationships of tasks.	McGraw and Harbison-Briggs, 1989 Meister, 1986 Stammers, et al, 1990
Failure Modes and Effects Analysis	The analyst determines what errors might occur in the informant's domain and what the consequences of such errors would be to the system	Henley and Kumamoto, 1981 Kirwan and Rea, 1986 Parry, 1986 Rasmussen, et al, 1981
Fault Trees	The analyst develops a fault tree that decomposes an undesired event into causal events and errors.	Green, 1983 Henley and Kumamoto, 1981 Parry, 1986 Veseley, et al, 1981
Information Flow Analysis	The analyst develops a flow chart of the information and decisions required to carry out the system's functions. The informant reviews and corrects the diagram.	Mancuso and Shaw, 1988 Meister, 1989 Stammers, et al, 1990
Diagram Drawing	The analyst draws a diagram representing processes in or states of the informant's domain. Possible formats include flow charts, activity charts, and system state\ action state diagrams	Fisher, et al, 1990 Hall, et al, 1994 Geiwitz, et al , 1988 Bainbridge, 1979

Table 3, Structured Approaches for System Behavior Analysis, adapted from Cooke, 1994.

Summary

A summary of the literature shows that there are various approaches to the development of models that can approximate the behavior of a complex system. Various techniques were presented as methodologies for developing the complex system model. Each technique involves, to greater or lesser degrees, the concept of the reduction of the system to its base components for simplification of the model of the system. The major theme in the literature was that, while these simple models approximate the complex system's behavior, the model itself was not a true representation of the complex system, but an approximation of the variables viewed from the observer's ontological stance.

There appeared to be a gap in the literature in describing a methodology that allows for a holistic view of the rich interaction of the complex system's subsystems and components once the system is deconstructed in to its basic elements. There is documentation in the literature for the development of "expert" systems models. The gap that forms the basis for this research is the lack of a methodology that shows that the knowledge of the interactions of the system can be derived from the system experts tacit knowledge and incorporated into the complex system model for a legacy complex system to better aid in the predictability of that system's propensity for failure.

CHAPTER III

CONCEPTUAL MODEL

Introduction

This chapter completes the literature funnel by introducing the maintenance context that the conceptual model must address. The conceptual model then addresses how both a reductionistic perspective and a holistic perspective can be gained from the model put forth through the use of expert knowledge in the development of a modified FMEA at the systems level.

Maintenance

Deshpande and Modak (2003) define maintenance as ensuring that [a] physical asset continues to fulfill its intended function. These functions of the assests and its desired standards of performance define the objectives of maintenance with respect to any asset. Very few systems are designed to operate without maintenance of any kind, and for the most part they must operate in environments where access is very difficult, or where replacement is more economical than maintenance (Lewis, 1994). Increasing complexity in design and high levels of automation has made detection of failure and repair of equipment more difficult (Robinson, 1987; Paz and Leigh, 1994; and Swanson, 2001). High levels of capital intensity associated with many systems have placed greater pressure on the maintenance function to rapidly repair equipment and prevent failures from occurring (Collins and Hull, 1986; Swanson 2001).

There are three classes of maintenance schemes: corrective, preventive and predictive (Swanson, 2003; Yang, 2001). Corrective maintenance occurs after a system has failed and repair to the system is necessary. Preventative maintenance involves the replacement of parts, adjustments to the system or changes to the system to improve the reliability of the system and prevent failure by staving off the effects of system aging. Predictive maintenance requires the assessment of the system by a system expert and unscheduled maintenance to prevent the possibility of the failure based on unrevealed system problems.

While time-based and MTTF practices are based on a window of opportunity and on the likelihood of a failure occurring during a specific time in the systems lifecycle in preventative maintenance (Lewis, 1994), predictive maintenance generally requires that technical experts evaluate the system in its entirety. Predictive maintenance is less costly than [corrective] emergency or preventive maintenance and results in less down time to perform adjustments, repair, and cleaning, when the established metric reaches a predetermined point, is scheduled with no disruption of the operation (Westerkamp, in Maynard 2001).

Often referred to as condition-based maintenance (Yang, 2002), predictive maintenance is initiated in response to a specific equipment condition. However it is that assessment of the condition over time that requires an expert evaluation based on the expert's experience with the equipment being maintained. In effect the experts are making reliability predictions of the system from a top down perspective of the system based on similar experience with like systems whose reliability is known to the exerts, rather than from the base parts level. According to O'Connor (1995) this type of predictive schema is one that is likely to be attained only if there is human commitment to it.

The literature presented in Chapter 2 suggests that an expert knowledge based, predictive maintenance system is feasible. This type of maintenance schema may be applied to quantify the system operability over a given time period to determine the need for assessment of the system, based on the collective knowledge of system experts, on the reliability of the system components and the ability of repair by the system's technicians.

A methodology that establishes a relationship between the knowledge base tightly held by the system experts, the data captured in the maintenance history of the complex system, and the behavior of the system was not prevalent in the literature. By establishing the relationship, a better determination may be made for the need for assessment of the entire system by experts to reveal potential unforeseen failures. Potential advantages of such a methodology are:

- Cost savings – Costs associated with the use of technical experts shifted to general maintenance personnel
- Reduction in failures – identifies possible causes of impending failures to warn of failure before it occurs
- Mission availability – decreases the time necessary to take system out of service for unnecessary assessments

Conceptual Model

In studying the complex maintenance system, and development of a model that approximates the system, the system must be decomposed to the basic failure sequences that are intended for study. However, this reduction in the system to its base components is not enough to understand the interactions of the system with its environment, nor does it provide the necessary picture of how the system and its human interface compensate to perturbations on the system. The systemic model must then include a component that addresses the holistic perspective of the system.

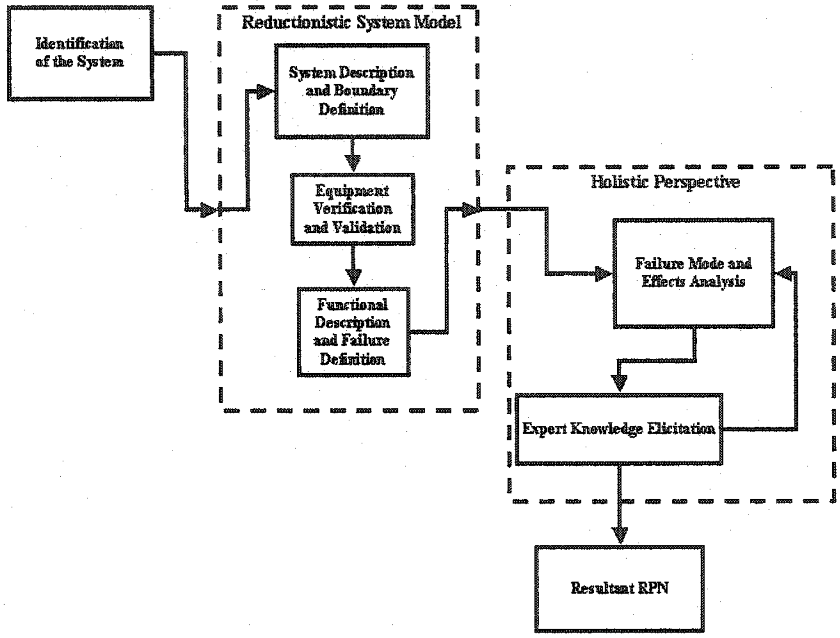


Figure 3, Conceptual Model for Maintenance System Analysis.

Development of the Reductionistic System Model

The concept of a Reductionistic Model is consistent with Stark (2000) and Verschuren (2002) in that the system must be reduced to its base components to allow for the necessary documentation of the system variables for scientific research to occur. The procedure used is based on COMNAVSURFLANT Proactive Maintenance Procedures Handbook (AMSEC LLC, 2003). The procedure presented allows for reductionism to establish the components contained with in a system to be studied, and the identification of failure modes. The procedure was reviewed and is consistent with the literature.

The first step in the development of the Reductionistic System Model is defining the system and its physical and functional boundaries. In this way a focused analysis can be accomplished. Expanding the boundaries too wide defeats the purpose of the study by introducing too many variables. The system definition is accomplished in three parts:

- Determine and verify the system component block diagram
- Determine and validate the system functional block diagram
- Create system functional top breakdown (TDBD) diagram.

The second step is equipment verification and validation. This requires the comparison of the configuration data (inventory and parts from the maintenance system for the repair/replacement of system components) to the functional TDBD. The result of this comparison is the creation of an inventory matrix of the component parts of the system. Discrepancies are resolved with site visits to the system or platform under question for validation and verification of the existence of the components under question.

The final step in the Reductionistic System Model is the development of the system functional description and failure definitions. The greatest difference in the development of this portion of the system model departs from conventional maintenance thinking is the realization that component failure does not equate to system failure as the system or sub system may have inherent redundancies that can compensate for the failure of a single component. Failure of system function is the focus of this step in development of the system model. The three major phases in this analysis is the development of:

- System functional description
- System functional failure definition and,
- The development of a system functional failure matrix.

This resultant is the structured failure matrix that allows the query of system experts on the behavior of the system as the result of a potential failure.

Holistic Perspective

The literature suggests that the use of FMEA (Failure mode and effects analysis) (US MIL-Std-1629A, 1980/1984) as a means to develop a knowledge basis (Barkai, 1999; Wirth et al, 1996;Yacoub and Ammar, 2002; Goossens and Cooke, 1997) to model the system. While Goossens and Cooke along with Yacoub and Ammar use the method as a means to identify potential risk in system failure in the design of complex systems, Wirth et al and Barkai elude to the use of the FEMA to generate diagnostic expert systems and knowledge-based support of systems analysis.

Most of the current FMEA literature focuses on use of FMEA with concurrent system design. Design FMEA is a standardized technique widely used in the automotive, aerospace and other industries that is used to identify prioritize and eliminate known and potential failures, problems and errors from systems under design before product release (Bowles, 1998; Lee, 2001) [Table 4].

Task	Method
Build FEMA Model Structure	Elaborate 'causal' chain failure dependencies; (Causes > Failure Modes > Effects)
Score and Prioritize	Assess Risk Priority Numbers (RPN); (failure frequency * end-effect severity * detection difficulty)
Decide and Act	Optimize design improvements, tradeoffs, test plans, manufacturing changes, etc.

Table 4, Design FMEA, adapted from Lee (2001).

Traditionally, this model is used to focus limited design resources on critical design tradeoffs and decisions leading to improved reliability, quality and safety (Stamatis, 1995). This iterative process is often used to influence design by identifying failure modes, assessing their probabilities of occurrence and their effects on the system, isolating their causes, and determining corrective action or preventative measures (Ebeling, 1997).

The systems under study for this research effort are at maturity levels that preclude this as a viable option to establish redesign parameters, however it appears that the use of this tool at a higher level to establish a knowledge base to elicit expertise in the system areas that are to be addressed will be invaluable. Development of a FMEA for each system uniquely particular to the class to which it belongs will vary dependant on the stage of the system's lifecycle. The primary application of FMEA in this instance is to translate a set of qualitative relationships that exist in the complex system, based on the widely held beliefs of the system stakeholders, into a quantitative data set (RPN – risk priority number).

A system level FMEA is a structured process to identify potential failures and the effect of these failures on system performance. The RPN is a critical factor, which considers equipment complexity, mission needs, performance criteria, redundant assets, consequences of failures, safety, legislated requirements and other comparable salient criteria. An RPN is developed by the selected technical/system experts to determine the relative impact of each failure mode of the FMEA. For this evaluation the RPN looks at three areas:

1. How often a Failure Mode is likely to occur

2. The mission degradation and/or downtime it would cause

3. The level of repair that would be needed to fix it

This is a departure from the tradition RPN design used in a research and development effort. By evaluating these parameters in the development of the RPN, the result yields a perspective not only on the physical system as initially designed, it incorporates the context in which the complex system exists within its environment, the rich interaction of the system on the meta-system within which it exists, the interaction of the human with the physical environment of the system and its effect on the system readiness via maintenance capability of personnel assigned to the system.

The RPN may then be used as a management decision support tool that contributes to determination of the appropriate assessing activity for a system. Assignment of assessments to the organizational level are made only when the following conditions are met:

1. Required assessment skills are within standard technical capability of the maintenance personnel
2. Requisite test equipment and assessment procedures are readily available

High RPNs indicate potential failures, which have a major system performance impact. Assessments for high RPN failures are assigned to technical experts. Assessments for lower RPN failures, which tend to have relatively minor system performance impact, can be assigned to the system's maintenance personnel. Before assigning an assessment to system's maintenance personnel the methodology confirms through an iterative process and dialogue with the technical experts that the required assessment skills are within standard technical capability of the maintenance personnel; the requisite test equipment and assessment procedures are readily available; and potential equipment failure will not create a safety hazard.

The predictive maintenance schema is now more narrowly focused toward the use of technical expertise only on those failure modes that dictate through the resultant high RPN.

Summary

The use of both the Reductionistic and Holistic perspectives can capture the complexities of a legacy system. Reducing the complex system to its base components to model the failure modes provide sufficient structure for the development of a holistic approach to quantify the experts knowledge. The presentation of the conceptual model allows for the use of the knowledge held by the experts by management in a manner that may be used to base decisions on whether assessment of the system is warranted.

CHAPTER IV

RESEARCH METHODOLOGY

Introduction

Before discussing the research methodology used in this effort, it is important to reiterate the problem statement, introduce the population details of the study and restate the research question prior to the discussion of the methods that will be used to test the conceptual model.

Frequently, large-scale maintenance of complex systems (i.e., a naval vessel) is based on the reduction of the system to its base subcomponents and the use of manufacturer-suggested, time-directed, preventative maintenance, which is augmented during the systems lifecycle with predictive maintenance which assesses the systems ability to perform its mission objectives. This maintenance scheme ignores the complexity of the system it tries to maintain. By combining the base components or subsystems into a larger system, and introducing human interaction with the system, the complexity of the system creates a unique entity that cannot be completely understood by basing predictability of the system to perform tasks on the reduction of the system to its subcomponents.

This chapter discusses the application of the conceptual model and the methods used in the deployment of the model in the controlled research environment. Hypotheses are put forth for the test of the model to predict the behavior of the system based on the holistic perspective of the experts. To evaluate the experts, a comparative is used that is based on historical records.

Scope of study

The conceptual model, as described in the pervious chapter, includes a variety of applications and approaches (e.g. Complex system modeling, the use of FMEA in maintenance practices, expert elicitation for model development). To test all these is beyond the scope of this dissertation. Furthermore, it is possible that the methodology presented will have different effectiveness for:

- Differences in system type
- System size
- Technical nature of the system
- Human interactions with the system
- Availability of data regarding the system
- And others

A population must be selected which will control for these factors, or these factors must be addressed in the analysis. In this research effort the first approach will be used. Several delimitations have to be made which will allow the problem to be constrained sufficiently. For purposes of this research and to test the model, the Low Pressure and Medium Pressure Air Compressor (LP-MPAC) systems on various ship platforms will be used. The LP-MPAC systems were selected, as previous work was available to support the research. This research will make use of previously collected data to test the use of the holistic modeling portion of the conceptual model. COMNAVSURFLANT has previously developed a guideline for the development of the theoretical modes of failure for their ship systems. Application of this guideline will aid in the selection of and development of the reductonistic systems model and will provide structure for testing the research hypothesis.

Research Question

Based on the literature discussed in the previous section, tools like FMEA exist to assist in the design of systems. Little or no methodology is apparent with respect to the decision process that encompasses the application of corrective actions for existing systems accounting for the degradation of the system, overtime, based on knowledge tightly held by system experts. The question to be answered by this research is: can a methodology that uses the expert knowledge, elicited from system experts through a high level FMEA, be used to create a knowledge based decision support system to aid in the assessment of legacy systems?

Population Details

Overview of SEMAT II Process

The Systems and Equipment Material Assessment Team (SEMAT II) visit is a condition based assessment program for hull, mechanical and electrical (HM&E) systems and equipment. This visit occurs simultaneously with the C5RA (a combat systems, command, control, communications and computer readiness, condition based assessment program). Current policy is to move toward the consolidation of redundant inspections and assessment visits to improve the availability of ships for deployment. SEMAT II visits are designed to be two-week visits comprised of civilian, military and contractor field service engineers to assess onboard equipment, offer technical repair expertise and provide deck-plate level training to ships personnel.

Scheduled on a once per maintenance cycle basis, the visit occurs four to six months prior to deployment following ships major availability for shipyard repair and overhaul. The visit is in support of a US Navy move toward a condition based maintenance program rather than a time directive maintenance program. Figure 4 contains the ship maintenance cycle and the position of SEMAT II in that process.

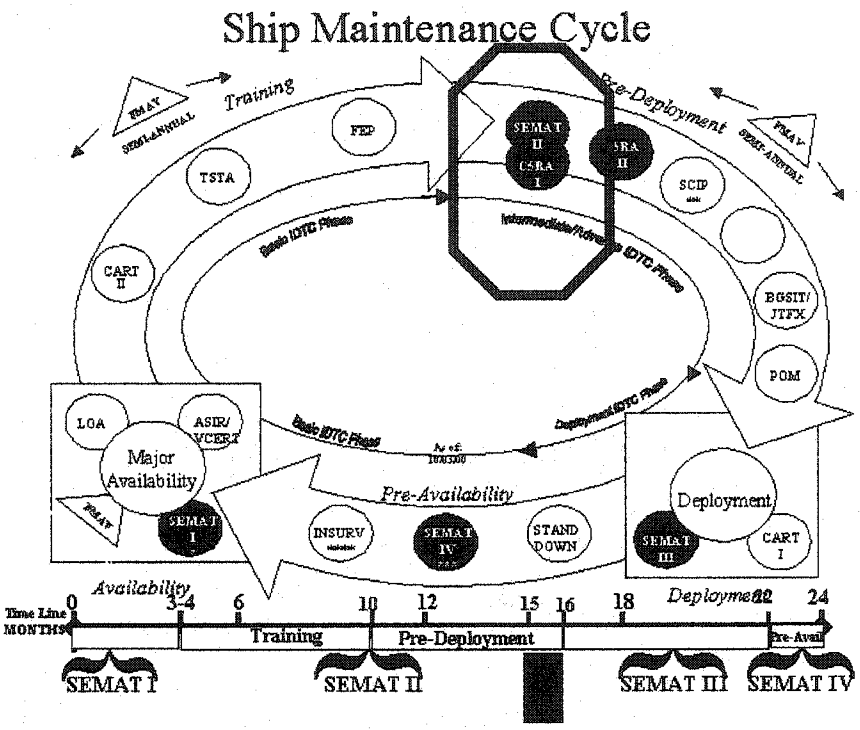


Figure 4, Ship Maintenance Schematic, source:
COMNAVSURFLANT internal document.

The cost of performing the SEMAT II/C5RA assessment and time limiting factors are compelling reasons to move toward an effective, knowledge/information-based, reliability system using a structured decision process and the data available from the Ships 3-M OARS system.

Use of Secondary Data

The existence of historical failure data allows for a benchmark for the research from which a conclusion may be drawn. This gives internal validity to the research, and a standard to provide a means of measure. To test the conceptual model, it will be necessary to uses secondary data from existing historical databases.

What is secondary data? Data may be described as primary or secondary. The researcher himself collects primary data. Secondary data is often collected by others and "re-used" by the researcher. The process of research involves some consideration of previous work in the same field. All researchers read and use the research of others. In the same way that it is possible for a researcher to review the previous work in any field and still go on to carry out original work, it is possible for a researcher to carry out a secondary analysis and still go on to carry out original work (Gorard, 2002). Secondary data analysis is being used extensively in many fields such as astronomy, high-energy physics, the genome project, statistics, economics, and psychological health surveys (Church, 2001; Keller and Warrack, 1997; Cooper and Schindler, 1998). Secondary data is a viable resource to aid the research process.

Speed and cost are the most obvious advantages of using secondary data. Since the data already exists, it is by definition generally quicker to 'collect', involving less travel and minimal cost (Gorard, 2002). Care should be taken when using secondary data, as errors may have been introduced as a result of the transcription or due to misinterpretation of the original terminology and definitions employed (Keller and Warrack, 1997).

Secondary data is generally used for three research purposes. First it fills a need for a specific reference or citation on some point – perhaps in a research proposal, to demonstrate why the proposed research fills a void in the knowledge base. It allows for a reference benchmark against which to test other findings. Second, secondary data is an integral part of a larger research study or of a research report to justify having bypassed the costs and benefits of doing primary research. Third, secondary data may be used as the sole basis for a research study, since in many situations one cannot conduct primary research because of physical, legal, or cost influences. Retrospective research often requires the use of published data (Cooper and Schindler, 1998).

In many studies the power of secondary data is allied to the flexibility of primary data techniques. One way in which all studies can gain from integrating secondary data is to set the context for the primary data. Even relatively large-scale data collection cannot compete in size and quality with existing records, so re-analysis of these records can be helpful in a variety of ways. It can provide the figures for each strata[um] in a stratified sample (else how do you know what proportions to use?). It can be used to assess the quality of an achieved population. These figures can then be used to weight the sample if there is a clear basis in its composition. Contextual secondary data can also be used to ague that a problem exists to be solved by other techniques, and to begin to describe the nature of that problem. (Gorard, 2002)

The most important limitation of secondary data sources is that the information may not meet your specific needs. Others have collected source material for their own purposes. Operational definitions will differ and may not be available for evaluation, units of measure are different, and different times may be involved or environmental stimuli may not be compatible. It may be difficult to assess the accuracy of the information because one knows little about the research design or the conditions under which the research occurred, unless the agent who collected the data is impeccably credentialed and has documented the procedures. (Cooper and Schindler, 1998) The investigator is dependent on other researchers' decisions regarding the population, sampling design, and measures used in data collection. Consequently, researchers must accept the limitations of the data set or not use that data set. Second, whatever measures were collected are the only ones for use. Each investigator must decide if the included measures are adequate and sufficient to answer the research question. (Mainous and Hueston, 1997)

Because not all data that comes from secondary sources is valid, Ormrod and Leady (2001) submit that one means of reducing the use of defective data is that there be a criteria for the admissibility of data. This issue has heightened importance in secondary data analysis because the investigator was not involved in the data collection (Mainous and Hueston, 1997). It is further compounded from the aspect that the secondary data may come from various sources that had a variety of collection methods. Therefore, to ensure the integrity of the research, standards for the acceptance of the secondary data needs to be established from the outset.

Specifically in this age of 'data-mining' from large databases, that the researcher has little control over the data that has been entered, it is critical that the process through which the data is to be elicited from the database is documented, clearly and stringently, to remove possible bias in the resulting data set. This process for the development of associative rules must, like the development of a complex system model, be an iterative process and must fit the context of the research methodology. Data and methodology are inextricably interdependent (Leedy and Ormrod, 2001).

In the development of the associative rules necessary to extract data from the database, the use of linguistic terms in a top down mining algorithm allows for the a progressively deepening approach to finding large interest item sets (Hong et al, 2003). Agrawal et al. (1993) propose several mining algorithms based on the concept of large item sets. In their research, the mining process was divided into two phases. In the first phase, candidate item sets were counted by scanning the database. If the data set was larger than a predefined threshold then the item set was determined a large item set. Item sets containing single items were processed first, large item sets were re-mined and filtered to reduce redundancies in the data entry and then segmented based on confidence intervals.

It is important to note that these procedures for defining the item set mirrors the concepts developed in systems model development. The systems architect should begin by addressing the what (system), how (sub-systems) and why (the wider-system or system environment) of the problem context (Checkland, 1999). The problem context developed is meant to give the systems architect a means to clearly identify the system that is to be studied. By casing an initial wide net, and through an iterative process, the researcher can accomplish the task of collecting a valid data set from the database. By using the existing structure of the operational system being studied for the research effort, a part-of-hierarchy may be developed that provides the linguistic filter necessary got capture the appropriate data from the initial data repository- wide scan; this can be used to aid in the development of the filtering algorithms necessary to eliminate unsuitable data. The researcher must ultimately decide what data resulting from this process must be willingly omitted, and document the reasons for omissions.

By administering the process in a consistent, well-documented manner, that resultant secondary data yielded from this filtration, has validity that has been gained through the stringently documented, consistent process established by the researcher prior to the mining of the data. Appendix E details the development of the secondary data used to validate the conceptual model.

Test of Hypothesis

This test may be preformed in a variety of ways. However for simplicity, the first test of the hypothesis will be a comparison of the consensus generated by the expert FMEA and the FMEA generated through historical data (figure 5) i.e. RPNE is equal to RPNH. This would support the research question posed, "Can a methodology that uses the expert knowledge, elicited from system experts through a high level FMEA, be used to create a knowledge based decision support system to stream line assessment of legacy systems?" However, for this question to be answered positively the RPN resulting from the expert could also be greater than the RPN developed from the historical data set, i.e. RPNE is greater than RPNH. Having an RPNE greater than or equal to RPNH would also imply that the expert judgment is more holistic in its assessment of the system, and that knowledge captured through the FMEA process can form the basis of a decision support system. Consequently the hypothesis statement can be represented as:

$$H_0 : RPN_E < RPN_H \quad H_1 : RPN_E \geq RPN_H \qquad \text{(Hypothesis 1)}$$

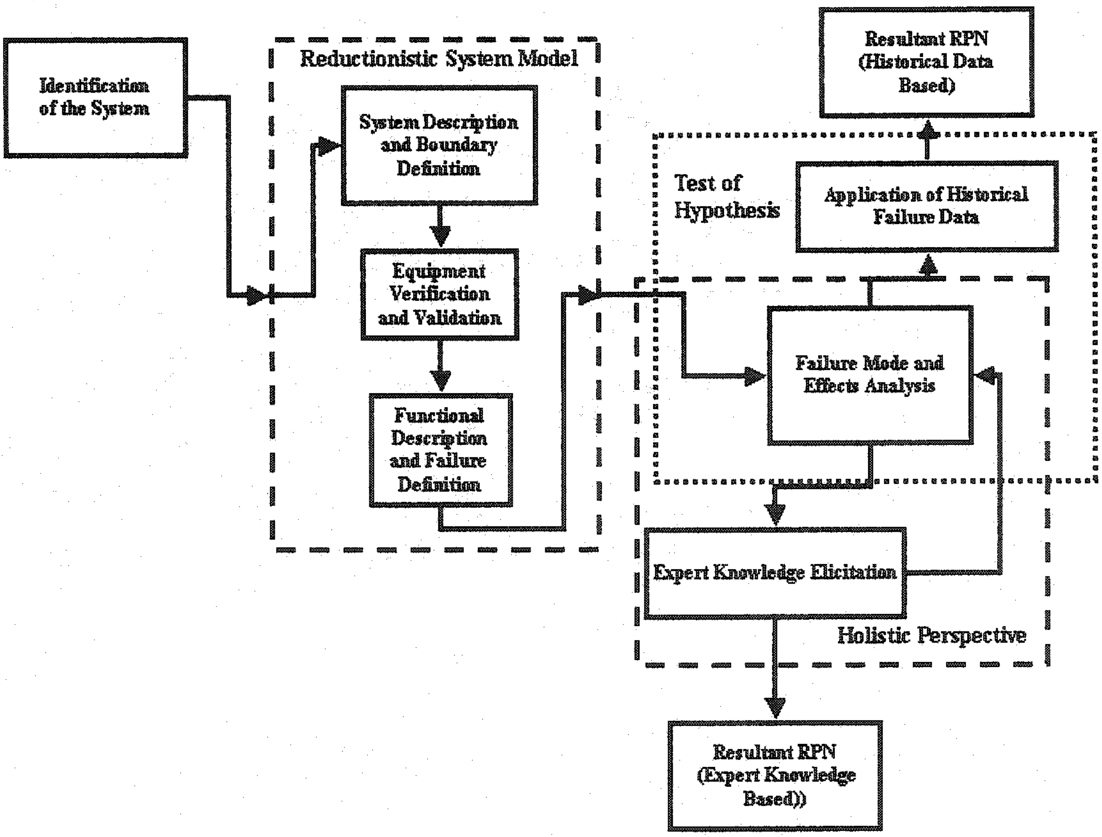


Figure 5, Test of Conceptual Model.

The same reasoning may be applied to the independent factors of the RPN model.The independent factors will also be compared to the historical data, yielding the following hypotheses to be evaluated by the research:

$$H_0 : S_E < S_H \qquad H_0 : R_E < R_H \qquad H_0 : O_E < O_H$$
$$H_1 : S_E \geq S_H \qquad H_1 : R_E \geq R_H \qquad H_1 : O_E \geq O_H$$

(Hypothesis 2) (Hypothesis 3) (Hypothesis 4)

It is expected that the factors will be greater in value from the experts due to their holistic perspective of the system under study.

Another hypothesis to be tested is "does a factor or factors exist that contribute to resulting RPN in a greater proportion." To test that hypothesis, the following hypotheses will also be evaluated:

$$H_0 : S_E * O_E < S_H * O_H \qquad H_0 : R_E * S_E < R_H * S_H \qquad H_0 : O_E * R_E < O_H * R_H$$
$$H_1 : S_E * O_E \geq S_H * O_H \qquad H_1 : R_E * S_E \geq R_H * S_H \qquad H_1 : O_E * R_E \geq O_H * R_H$$

(Hypothesis 5) (Hypothesis 6) (Hypothesis 7)

Again it can be presumed that the expert having a more holistic view of the system will devise a greater value in the consensus due to their holistic view of the system. The comparison of the expert to the historical RPNs provides an aggregation of the differences between the models. This allows for the reduction of the need to assess failure modes in which the historical and the expert are in concurrence and conserve resources to address the disparity between the resultant RPNs to achieve greater efficiency in the overall assessment of the system being studied.

Selection of Statistical Techniques

Siegel (1957) suggests that the choice among statistical test which might be used with a given research design should be based on the these three criteria:

1. The statistical model of the test should fit the conditions of research.
2. The measurement requirement of the tests should be met by the measures used in the research

3. From among those tests with appropriate statistical models and appropriate measurement requirements, that test should be chosen which has the greatest power efficiency.

Within the category of inferential statistics, specific analytic techniques are classified as either parametric or nonparametric. Parametric include such widely recognized tests as the Student's *t* test and the analysis of variance (ANOVA). Researchers using these and other parametric statistics must test several assumptions with regard to the coding and distribution of the variables they are studying. In most cases, parametric statistics require that data be normally distributed, that the variance is equal (i.e., homogeneous) in the data set and the dependent variables be continuous in nature, measured on either an interval or ratio scale (Fitzgerald et al, 2001)

Nonparametric techniques are generally used to test ranked data. Rather than testing to determine whether the μ_1 and μ_2 differ, it tests whether the population locations differ. Additionally, if the data are non-normally distributed, t-tests are invalid. Nonparametric techniques may be used as well in this instance.

In the selection of a measure to provide verification and validation of research data, various statistical models were evaluated for use in this endeavor. Figure 6 provides the logic used in choosing an appropriate statistical methodology.

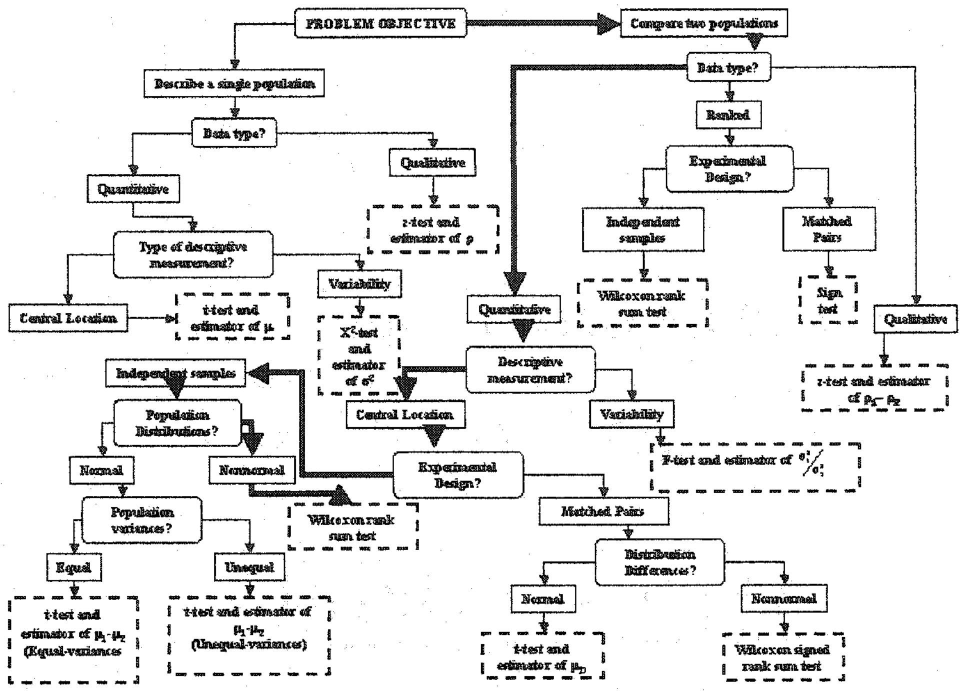


Figure 6, adapted from Keller, K. and B. Warrack, *Statistics for Management and Economics*, 4th Ed. (do not print in color)

Following the logic of figure 6, it is noted that the statistical test model used will be a Wilcoxon rank sum test, a nonparametric statistical test. There are obvious drawbacks to the use of this type of analysis. Nonparametric statistical models are not as ridged as their parametric counterparts. Therefore, the conclusions that may be drawn from them are more general in nature when using them to elicit statistical inference. However, it allows for the use of hypothesis testing on data that is nonnormally distributed. Additionally, appropriate parametric techniques will be used to develop inference in the absence of an appropriate non-parametric statistical method.

Detailed Research Approach

The Reductionistic System Model for the LP-MPAC, and the Historical Data used to populate the Statistical RPN Comparative, was developed through a joint effort with

COMNAVSURFLANT, AMSEC LLC, SUPSHIP Portsmouth and FTSCLANT. For this effort wherever the data used was from a secondary source, the procedure used to originally collect the data has been reviewed for consistency with the conceptual model and the literature. The necessary procedures for the collection of the secondary data are abridged in this narrative and data sources are provided for reference in Appendix E.

System Identification

Validation of the conceptual model, as previously outlined, will be done using the Low Pressure and Medium Pressure Air Compressor (LP-MPAC) systems on various ships in the US Navy.

The Reductionistic System Model for the LP-MPAC, and the Historical Data used to populate the Statistical RPN Comparative, was developed through a joint effort with COMNAVSURFLANT, AMSEC LLC, SUPSHIP Portsmouth and FTSCLANT. The method used to develop the Reductionistic System Model is documented in the COMNAVSURFLANT Proactive Maintenance Procedures Handbook (AMSEC LLC, 2002). The results of the development of the Reductionistic Model for the LP-MPAC are synopsized from internal COMNAVSURFLANT documents (LP-MP Failure Mode Report, August 2002), for consistency in the research.

System Description

The low-pressure air plant and systems supply air at required pressure for use in non-critical ship service air systems (those systems which can tolerate and operate satisfactorily with interruption of the air service) and vital control air systems. In SURFLANT, medium pressure air plants and systems typically supply air at required pressure for services and equipment such as, but not limited to:

1. Propulsion diesel starting
2. Diesel generator starting
3. Sea chest blow, whistle
4. Pneumatic clutch
5. Shaft brakes

Each low and medium pressure air plant is typically shipped from the manufacturer as a "skid " mounted unit. Some of these air plants have dehydrators and receivers mounted on the skid while others have these components installed downstream. For the purpose of this analysis, the study boundary for the low and medium pressure air plants will consist of all components, piping and associated controls between the air inlet up to and including any dehydrators installed prior to an air receiver. The air receiver will be outside of the study boundary. The following major components are considered to be within the air plant study boundary: Electric drive motor and motor controller, drive gear or coupling, air filter/silencer, compressor assembly, oil pump, moisture separators, dehydrators (LPACs only), heat exchangers/coolers, temperature and pressure sensors, associated gages, valves, hoses and piping.

SURFLANT uses reciprocating compressors (RCP-M) for their medium pressure compressed air plants and uses reciprocating (RCP-L), NAXI Rotary Helical Screw (RHS-N) and STAR Rotary Helical Screw (RHS-S) compressors for their low-pressure compressed air plants. The component block diagrams for these air plants are illustrated in Figures 7, 8, 9 and 10.

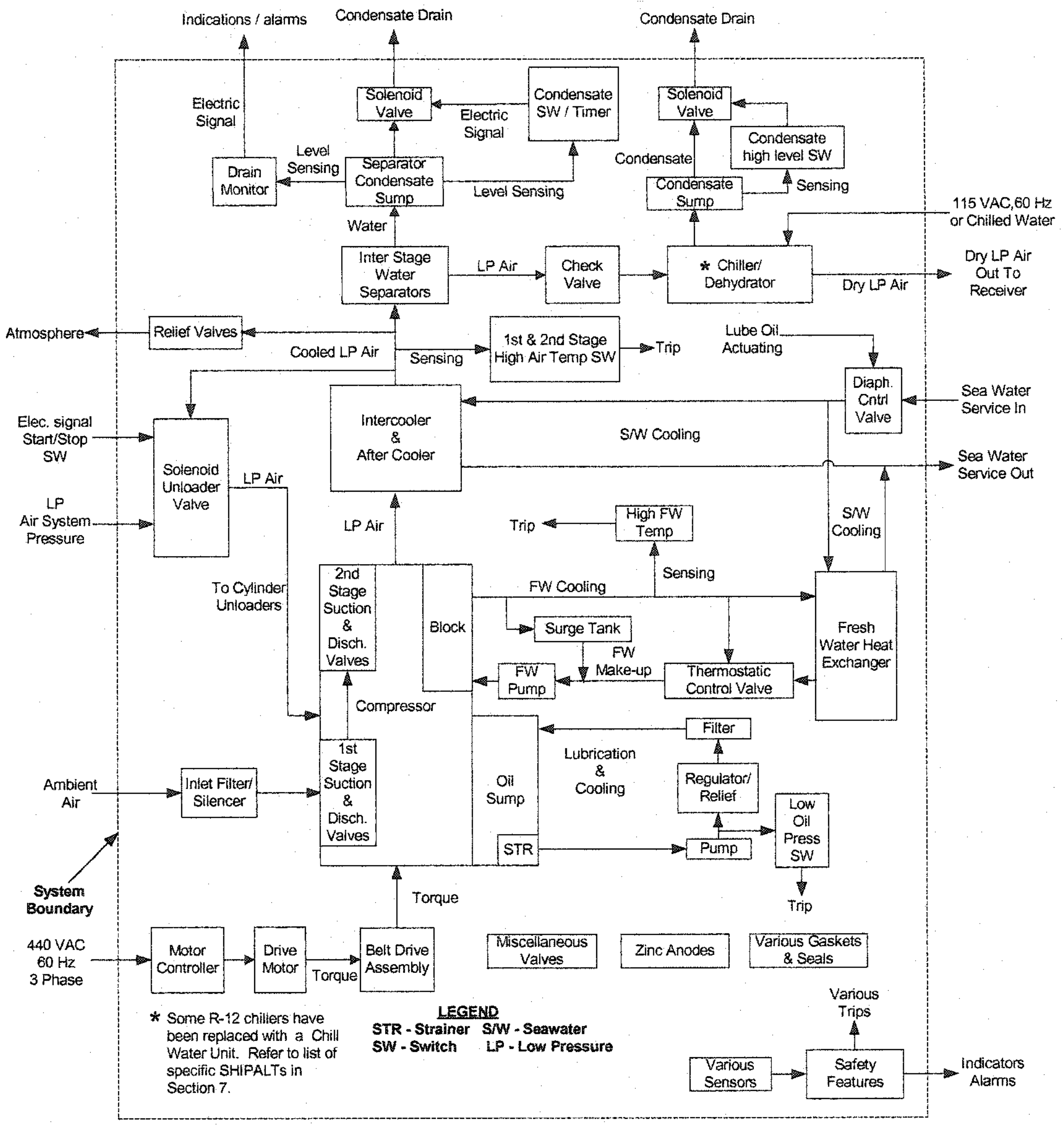
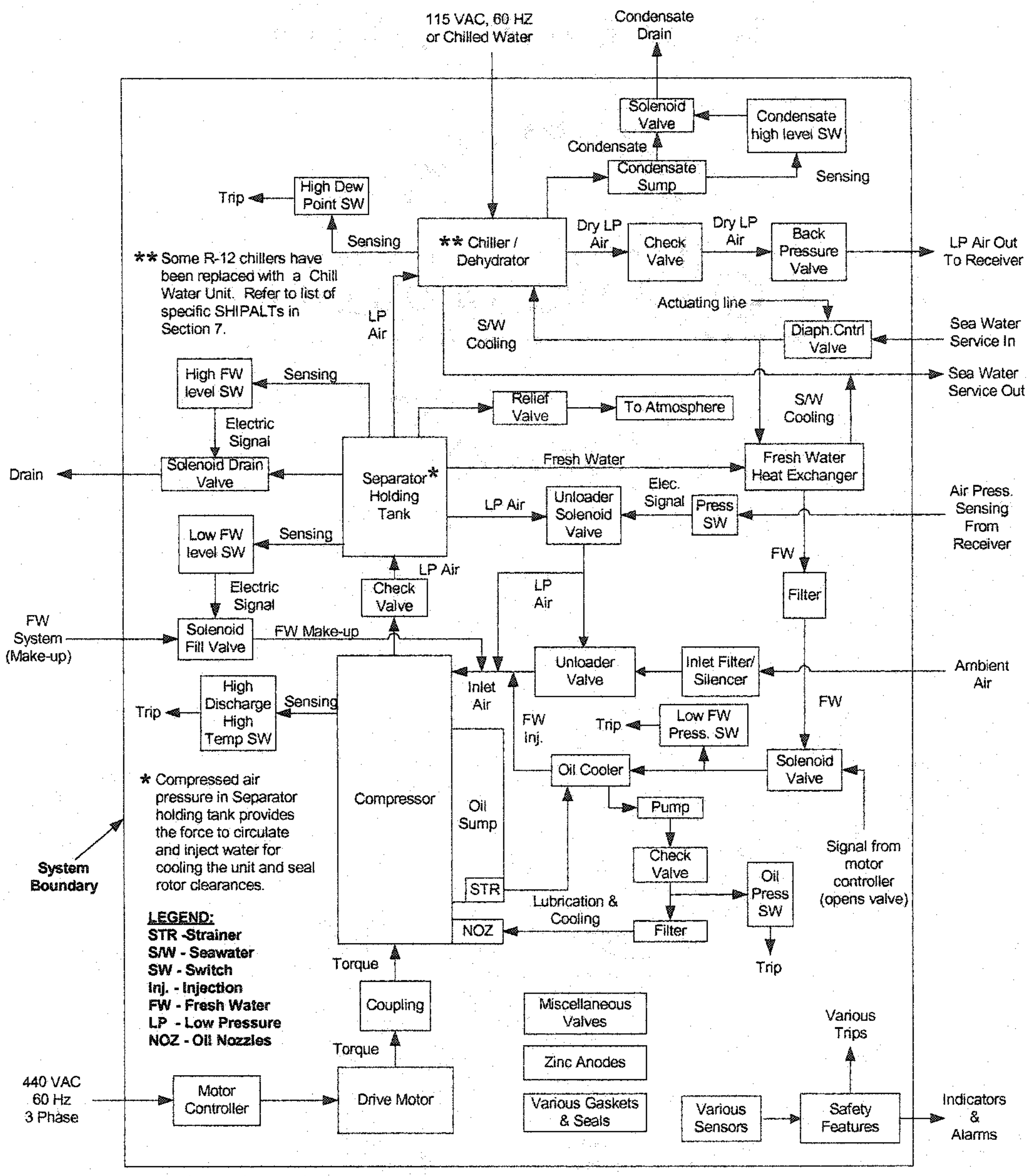


Figure 7, Component Block Diagram - Low Pressure Reciprocating Air Plants, COMNAVSURFLANT internal document.

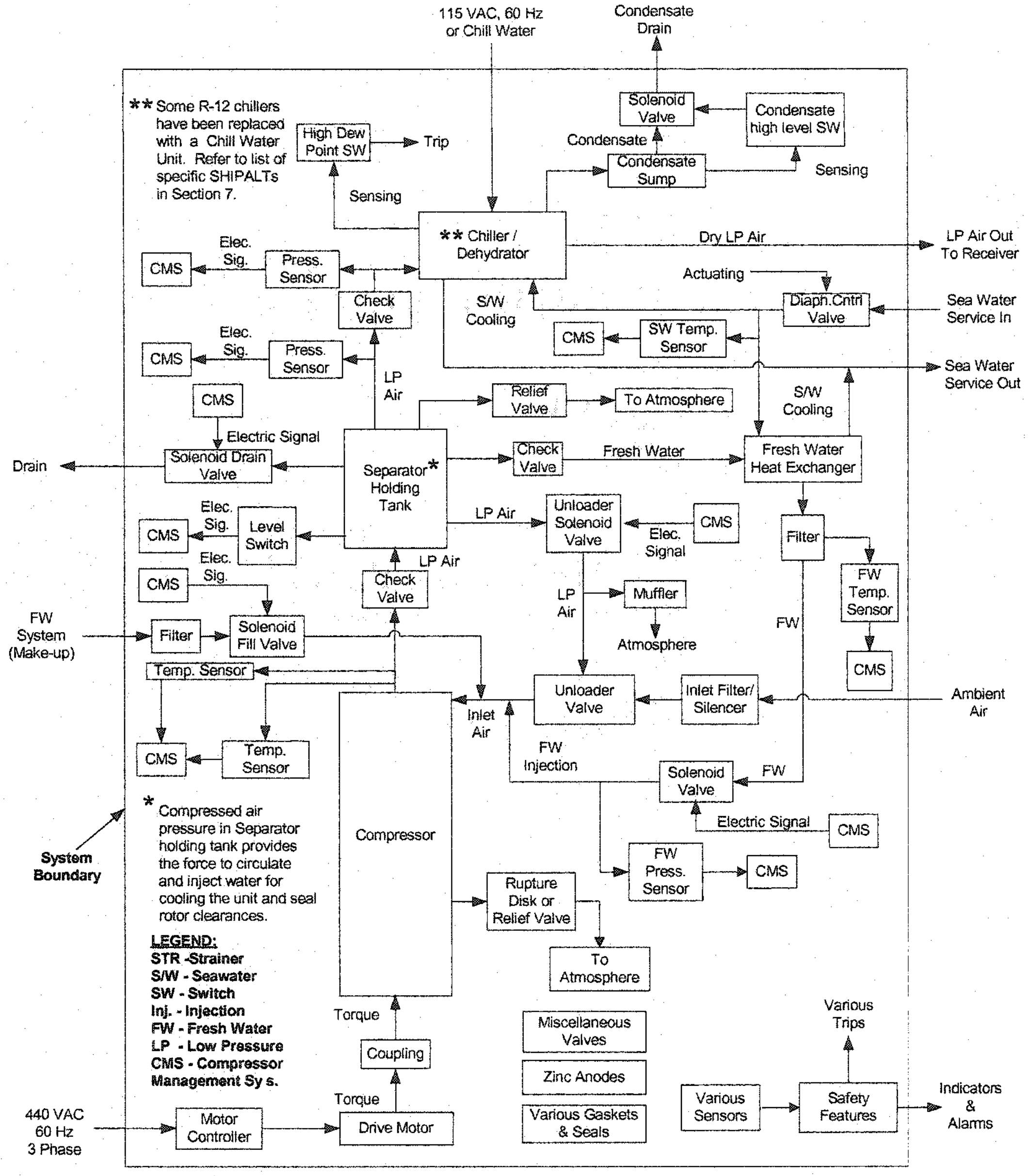


** Some R-12 chillers have been replaced with a Chill Water Unit. Refer to list of specific SHIPALTs in Section 7.

* Compressed air pressure in Separator holding tank provides the force to circulate and inject water for cooling the unit and seal rotor clearances.

LEGEND:
STR -Strainer
S/W - Seawater
SW - Switch
Inj. - Injection
FW - Fresh Water
LP - Low Pressure
NOZ - Oil Nozzles

Figure 8, Component Block Diagram - Low Pressure Rotary Helical Screw (NAXI) Air Plants, COMNAVSURFLANT internal document.



** Some R-12 chillers have been replaced with a Chill Water Unit. Refer to list of specific SHIPALTs in Section 7.

* Compressed air pressure in Separator holding tank provides the force to circulate and inject water for cooling the unit and seal rotor clearances.

LEGEND:
STR -Strainer
S/W - Seawater
SW - Switch
Inj. - Injection
FW - Fresh Water
LP - Low Pressure
CMS - Compressor Management Sy s.

Figure 9. Component Block Diagram - Low Pressure Rotary Helical Screw (STAR) Air Plants, COMNAVSURFLANT internal document.

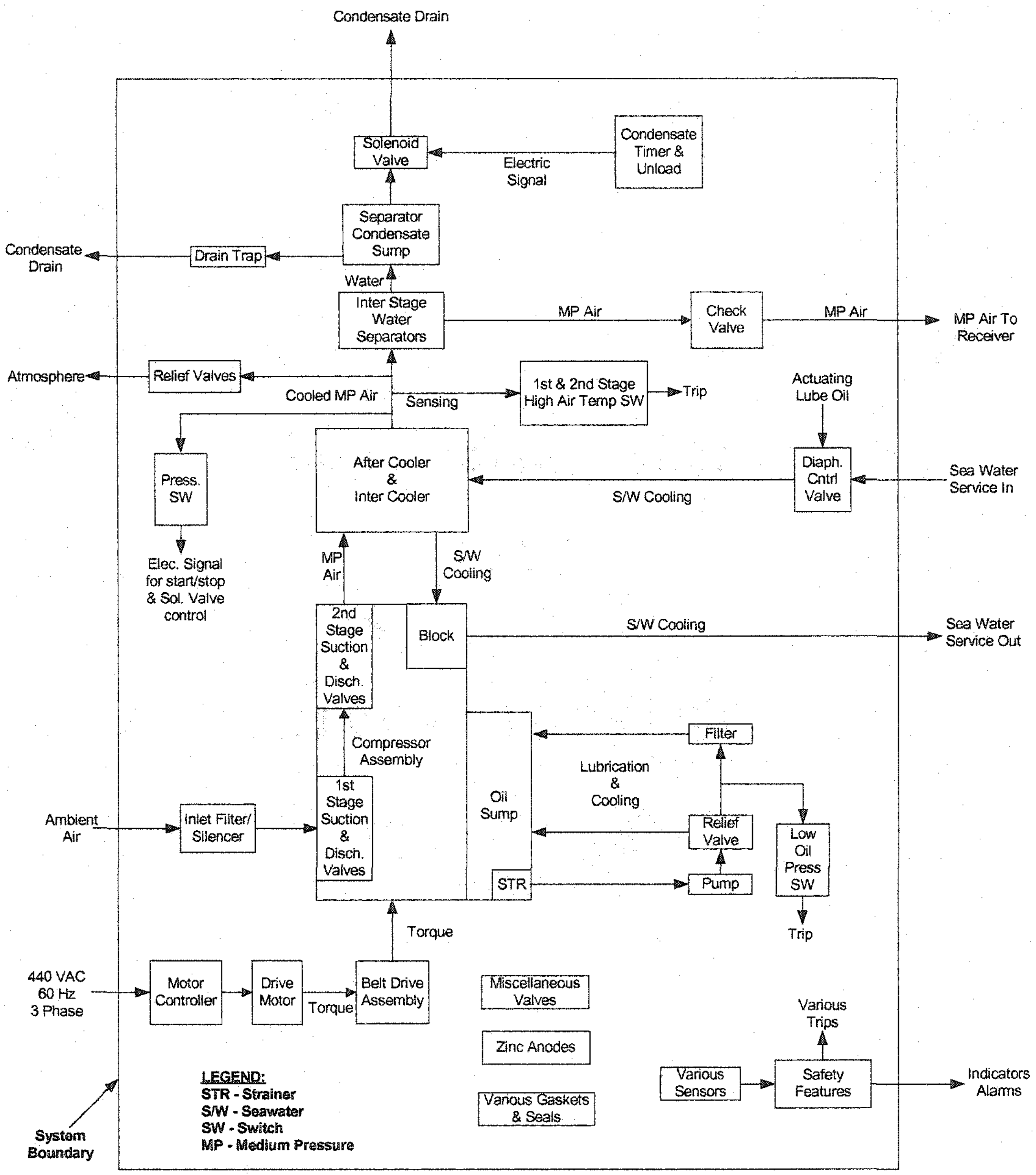


Figure 10, Component Block Diagram - Medium Pressure Reciprocating Air Plants, COMNAVSURFLANT internal document.

Functional Diagram

The low and medium pressure air plants are used to supply air to shipboard low and medium air pressure systems and to maintain the system pressure at the desired level. Ships in the current Force have low pressure and medium pressure air plants rated at 100-150 PSI and 600 PSI respectively. A functional block diagram is presented in Figure 11.

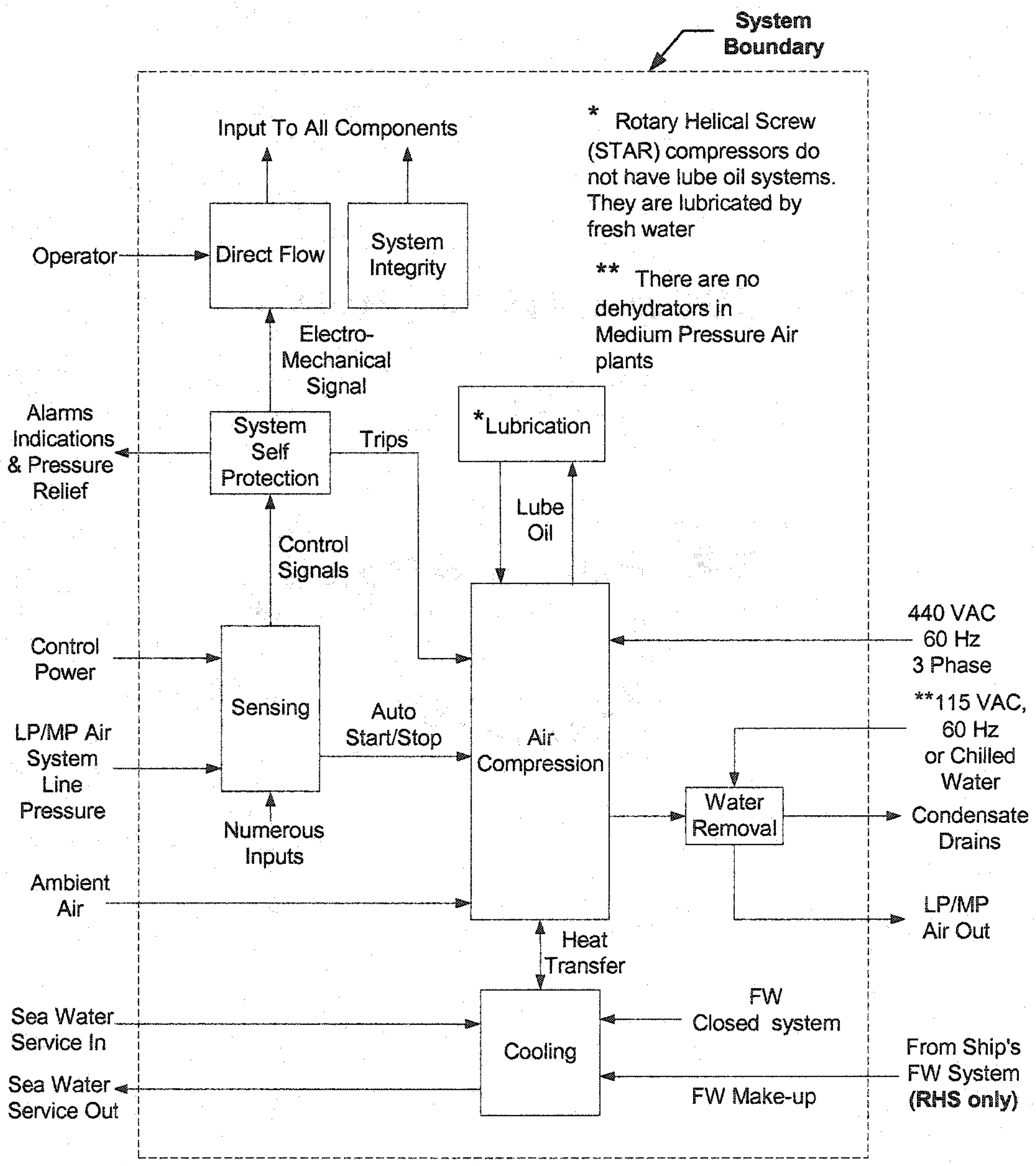


Figure 11, Low and Medium Pressure Air Plant Functional Block Diagram, COMNAVSURFLANT internal document.

Functional Topdown Breakdown

Figure 12 illustrates the relationship of the various components of Low Pressure and Medium Pressure Air Plants.

Cooling

1. Oil Pump
2. Oil Sump
3. Fresh water (FW)pump (Reciprocating)
4. FW separator/holding tank (Rotary Helical Screw)
5. FW heat exchanger
6. FW surge tank (Recip.)
7. Intercoolers (Reciprocatimg)
8. Aftercoolers (Reciprocating)
9. Fresh water injection ring (Rotary Helical Screw)
10. FW filter (Rotary Helical Screw)
11. Diaphragm control valve
12. FW thermostatic control valve (Reciprocating)

Direct Flow

1. Solenoid valves
2. Check valves
3. Diaphragm control valves (Seawater)
4. Thermostatic control valves (Fresh water)
5. Back pressure valves
6. Miscellaneous valves

System Integrity

1. Piping/hoses
2. Various component casings and housings
3. Miscellaneous valves
4. Various gaskets & seals

Water Removal

1. Water separators
2. Chiller/dehydrators
3. Drain monitors
4. Solenoid drain valves
5. Condensate sump

Lubrication

1. Oil sump
2. Oil filter
3. Oil pump
4. Check valve
5. Oil strainer
6. Oil cooler (RHS-N)
7. Oil spray nozzles (RHS-N)
8. FW Sep./Hold tank (RHS-STAR)
9. FW filter (RHS-STAR)

System Self Protection

Rotary Helical Screw

1. Oil pressure switch
2. High injection water level Trip
3. Low injection water level Trip
4. Low injection water pressure Trip
5. High condensate water level switch
6. High dew point temperature switch (condensate sump)
7. Receiver high pressure trip
8. High air temperature switch
9. Relief valves
10. Zinc anodes
11. Compressor high discharge pressure trip (STAR)
12. High compressor discharge temperature trip (STAR)

Reciprocating

1. First stage discharge high air temperature switch
2. Second stage discharge high air temperature switch
3. First stage high condensate level shutdown switch/probe
4. Second stage high condensate level shutdown switch/probe
5. Low oil pressure shutdown
6. Condensate drain timer relays
7. FW high temperature switch
8. Relief valves
9. Zinc anodes

Air Compression

1. Compressor assembly
2. Belt Drive assembly (Reciprocating)
3. Coupling (Rotary Helical Screw)
4. Drive motor
5. Motor controller
6. Unloading valve
7. Inlet filter /silencer

Sensing

1. Various sensors
   - Air discharge pressure
   - Heat exchanger pressure differential
   - Oil pressure
   - Crankcase oil temp
   - High FW cooling water temp
   - Sea water discharge temp
   - High air temperature
   - Cooling FW supply temp
   - Sea water inlet temperature
   - Moisture separator drain level (Reciprocating)
   - Dehydrator failure indicator (Rotary Helical Screw)
   - Dehydrator CondensateWater Level
   - Injection tank water level (Rotary Helical Screw)
   - Dew point (Rotary Helical Screw)
   - FW injection pressure (Rotary Helical Screw)

Figure 12, Low and Medium Pressure Air Plant Functional Top-down Breakdown.

Equipment Verification And Validation

An Reliability Centered Maintenance (RCM) Analyst, with assistance from a Data Analyst, verified and validated equipment contained within the defined system. They inventoried and documented the equipment/components of the system, comparing the developed component diagrams and the configuration data from the Maintenance Management Information System (MMIS). Ship Work Line Item Number (SWLIN) and Allowance Parts List (APL). This resulted in the creation of a master matrix that allows segregation of discrepancies into APL and Unit Identification Code (UIC) or ship class specific data. This matrix is used to determine the "bad actors" within the groups, cost and downtime comparisons, etc. Additionally, this determined the relative accuracy/completeness of the configuration data in the MMIS. There are three phases to this step of the process:

- Compare configuration data to the component block diagram comparison,
- Perform site validation, if required,
- Create inventory matrix / matrices.

Low and Medium Pressure Air Plant Population Data

In order to identify all applicable low and medium pressure air plants used in the Force, a query was performed on the Ship Configuration and Logistic Support Information System (SCLSIS) using the following Ship Work Line Item Numbers (SWLIN):

- 55120 – Air System, Low and Medium Pressure
- 55121 – Air System, Low and Medium Pressure
- 55152 – Compressors, MP Air and
- 55153 – Compressors, LP Air

This yielded a SURFLANT inventory of all low and medium pressure air plants by APL, ship class, hull number and compressor type Reciprocating (RCP), Rotary Helical Screw–STAR (RHS-S), Rotary Helical Screw-NAXI (RHS-N). The data date was 29 March 2002. The data used is not provided for reference due to military classification. During the equipment verification and validation some discrepancies in the SCLSIS data were found. Physical verification was performed. Data was adjusted to reflect the results of the physical verification.

Functional Description/Failure Definition

System Functional Failure is the inability of a system to meet a specified performance standard. A complete loss of function is clearly a functional failure, as is the inability to perform at the minimum level defined as satisfactory. All functional failures are not equal, because they do not have equal effects on the mission or safety of the ship. To accomplish this step of the process, it is necessary to further define the functions and associated functional failures for the system. Functional failures are quantified by determining what is too much, too little or degraded functional outputs for the system. In the Navy there is an operational aspect to this process in that functional failure often presents itself as a loss of mission area, which must be reported via the Casualty Reporting (CASREP) system. Functional failures can often be thought of as leading to C3 or C4 CASREP level failures.

Once all function definitions are determined, each is given a sequential number and added to a matrix. The number assigned will be used for tracking purposes throughout the rest of the study. The product of this step of the process is the completion of a list or matrix of system function and functional failure definitions. Table 5 provides a list of the low and medium pressure air plant system functions and their respective system functional failures. This matrix is critical to developing the theoretical system failure modes.

System Functional Description	**System Functional Failure Definitions**
1. Air Compression	1A No Pressure, No Capacity[a]
	1B Low Pressure[b], Low Capacity[a]
	1C Pressure Satisfactory, Low Capacity[a]
2. Cooling	2A No cooling
	2B Inadequate cooling
	2C Excessive cooling
3. Lubrication	3A No lubrication
	3B Inadequate lubrication
4. Direct Flow (Air or Fluids)	4A No flow (Air or Fluids)
	4B Incorrect flow (Air or fluids flow to incorrect location)
	4C Restricted flow
5. System Self Protection	5A Casualty exists, no shutdown
	5B Casualty does not exist, shutdown occurs
	5C Casualty exists, shutdown too slow
6. Sensing	6A No sensing
	6B Incorrect sensing
7. System Integrity	7A No containment (rupture)
	7B Partial containment (leak)
8. Water Removal	8A Moisture content too high

Notes:

a. A functional failure for "low capacity" is 25% below rated value.

b. A functional failure for "low pressure" is defined as a condition where the output pressure cannot reach the compressor unloading pressure with a light load condition.

Table 5, LP-MPAC Functional Failure Matrix, Adapted from COMNAVSURLANT LP-MP Report, 2001.

Failure Mode Determination

This step of the process is an analysis of the failure modes and maintenance strategy associated with the predominant failing component of the system. It was conducted by the Reliability Centered Maintenance (RCM) Analyst, and involves a detailed theoretical and scientific engineering look at each of the failures defined previously, with a goal of narrowing the field down to the most predominant failing component(s) and associated predominant failure mode(s) of the system. This is accomplished through a process of theoretical analysis, followed by comparison and grouping of actual maintenance data.

Determine Theoretical Failure Modes

The first step is designed to determine a list of the *theoretical* failure modes for each system component associated with each functional failure of the system as determined previously. These failure modes are generated from the system technical manuals, NSTM (Naval Ships Technical Manual) chapters, system specifications, and subject matter expert interviews. Using the Functional Failure Matrix, Table 5, a list of theoretical failure modes was generated and provided in Table 6. The table lists each Functional Failure and the most probable theoretical failure modes that would affect the functionality of the low and medium pressure air plants. Each of the theoretical failure modes is assigned a unique Failure Mode Code (FMC) for accounting purposes.

Table 6, Theoretical Failure Modes.

System Functional Failure Definition	Theoretical Failure Modes
1A No Pressure, No Capacity	**Reciprocating/Rotary Helical Screw** 1A1 Motor failure 1A2 Shutdown switch failed in shutdown position 1A3 Motor controller failure **Reciprocating Only** 1A4 Drive Belt(s) broken 1A5 Pulley failure 1A6 Piston failure 1A7 Piston ring melted / seized 1A8 Piston cracked 1A9 Connecting rod bent 1A10 Connection rod bearing failure 1A11 Crankshaft bent, broken /cracked **Rotary Helical Screw Only** 1A12 Rotor set seized 1A13 Rotor bearing failure 1A14 Rotor timing gears failure (RHS-N only) 1A15 Unloading system fails 1A16 Coupling failure 1A17 Injection cooling/sealing water (low Pressure)

Table 6, Theoretical Failure Modes.

System Functional Failure Definition	Theoretical Failure Modes
1B Low Pressure, Low Capacity	**Reciprocating/Rotary Helical Screw** 1B1 Unloader valve partially open 1B2 Relief valve (activating too low a pressure) 1B3 Relief valve (failed open) 1B4 Drain valves partially open 1B5 Air filter/ silencer restricted 1B6 Piping or gaskets Leaks **Reciprocating Only** 1B7 Piston rings worn or broken 1B8 Blown head gasket 1B9 Piston cylinder liner worn 1B10 Suction / discharge valves leaking 1B11 Loose/ slipping drive belts 1B12 Piston air rod packing worn **Rotary Helical Screw Only** 1B13 Rotor set worn 1B14 Blown casing gasket
1C Pressure Satisfactory, Low Capacity	**Reciprocating/Rotary Helical Screw** 1C1 Piping or gaskets Leaks 1C2 Drain valves open or partially open 1C3 Outlet check valve (opening restricted) **Reciprocating Only** 1C4 Suction /discharge valves leaking 1C5 Piston rings worn 1C6 Cylinder unloader fails in open position **Rotary Helical Screw Only** 1C7 Rotor set worn 1C8 Unloader valve partially opened

Table 6, Theoretical Failure Modes.

System Functional Failure Definition	Theoretical Failure Modes
2A No cooling	**Reciprocating/Rotary Helical Screw** 2A1 Air line restriction 2A2 FW heat exchanger (SW side) blocked (All except RCP-M) 2A3 FW heat exchanger (F/W side) blocked (All except RCP-M) 2A4 No fresh water coolant (All except RCP-M) 2A5 Lube oil pump failure (All except RHS-S) **Reciprocating Only** 2A6 Thermostatic valve failure 2A7 Fresh water pump failure 2A8 Clogged oil strainer **Rotary Helical Screw Only** 2A9 Fresh water injection cooling water system failure
2B Inadequate cooling	**Reciprocating/Rotary Helical Screw** 2B1 FW heat exchanger restricted or air bound (S/W side) 2B2 FW heat exchanger restricted or air bound (F/W side) 2B3 Oil pump worn (All except RHS-S) 2B4Low fresh water coolant level (All except RCP-M) **Reciprocating Only** 2B5 Fresh water pump worn (All except RCP-M) 2B6 Intercoolers / Aftercoolers (S/W side restricted) 2B7 Thermostatic control valve malfunctioning **Rotary Helical Screw Only** 2B8 Fresh water injection cooling/sealing water system failure (low pressure/flow) 2B9 Separator holding tank leak (Low pressure) 2B10 Oil flow restricted (RHS-N only)
2C Excessive cooling	**Reciprocating/Rotary Helical Screw** 2C1 Excessive seawater cooling water flow

Table 6, Theoretical Failure Modes.

System Functional Failure Definition	Theoretical Failure Modes
3A No lubrication	**Reciprocating/Rotary Helical Screw** 3A1 Lube oil pump failure (All except RHS-S) 3A2 No oil level (All except RHS-S) **Reciprocating Only** 3A3 Clogged oil strainer **Rotary Helical Screw Only** 3A4 Oil cooler (oil side) blocked (RHS-N only) 3A5 No Fresh water injection (RHS-S only)
3B Inadequate lubrication	**Reciprocating/Rotary Helical Screw** 3B1 Low oil level (All except RHS-S) 3B2 Oil pump worn (All except RHS-S) 3B3 Oil filter clogged (All except RHS-S) **Reciprocating Only** 3B4 Clogged oil strainer **Rotary Helical Screw Only** 3B5 Oil cooler (oil side) restricted (RHS-N only) 3B6 Clogged oil nozzles (RHS-N only) 3B7 Low fresh water injection pressure (RHS-S only)
4A No flow (Air or fluids)	**Reciprocating/Rotary Helical Screw** 4A1 Improper valve position (shut) 4A2 Valve failure (failed shut)
4B Incorrect flow (Air of fluids flow to incorrect location)	**Reciprocating/Rotary Helical Screw** 4B1 Improper valve position (shut/open) 4B2 Valve failure (leakage) 4B3 Valve failure (failed shut) 4B4 Valve failure (failed open)
4C Restricted flow	**Reciprocating/Rotary Helical Screw** 4C1 Valve in mid-position 4C2 Clogged strainer 4C3 Cooling system restricted (S/W side) 4C4 Cooling system (FW side) restricted (Except RCP-M) 4C5 Air filter/silencer restricted **Rotary Helical Screw only** 4C6 Injection water filter restricted

Table 6, Theoretical Failure Modes.

System Functional Failure Definition	Theoretical Failure Modes
5A Casualty exists, no shutdown	**Reciprocating/Rotary Helical Screw** 5A1 Trips do not activate (Refer to Table 5-2) 5A2 Relief valve (activating pressure too high)
5B Casualty does not exist, shutdown occurs	**Reciprocating/Rotary Helical Screw** 5B1 Trips activate without failure condition present (refer to Table 5-2)
5C Casualty exists, shutdown too slow	**Reciprocating/Rotary Helical Screw** 5C1 Sensing lines fouled **Reciprocating Only** 5C2 Oil pressure sensing timer failure **Rotary Helical Screw Only** 5C3 Injection water /oil pressure timer failure
6A No sensing	**Reciprocating/Rotary Helical Screw** 6A1 Pressure sensing – Sensing line is pinched, clogged, kinked, cut or sensing valve closed 6A2 Temperature sensing – Sensor is fouled or cut 6A3 Level sensing – Mechanical linkage binding, contacts 6A4 Sensor opened or shorted (electrically) 6A5 Wiring harness cut/shorted
6B Incorrect sensing	**Reciprocating/Rotary Helical Screw** 6B1 Pressure sensing – Sensing line is pinched, clogged or kinked 6B2 Temperature sensing – Sensor is fouled 6B3 Level sensing – Mechanical linkage binding, contacts 6B4 Sensor out of calibration
7A No containment (rupture)	**Reciprocating/Rotary Helical Screw** 7A1 Head / casing gaskets seals blown 7A2 Head / casing cracked 7A3 Hoses/Piping ruptured **Reciprocating Only** 7A4 Interstage cooler rupture **Rotary Helical Screw Only** 7A5 Rupture disk ruptured (RHS-S only)

Table 6, Theoretical Failure Modes.

System Functional Failure Definition	Theoretical Failure Modes
7B Partial containment (leak)	**Reciprocating/Rotary Helical Screw** 7B1 Head / casing gaskets/seals leak 7B2 Gaskets/seals leak 7B3 Hoses/piping cracked, deteriorated or mechanical joint failure **Reciprocating Only** 7B4 Interstage cooler leak **Rotary Helical Screw Only** 7B5 Oil / Water seal failure (RHS-N only)
8A Moisture content too high	**Reciprocating only** 8A1 Condensate/water level too high in separator 8A2 Condensate drain failure **Rotary Helical Screw only** 8A3 Water level too high in separator holding tank 8A4 Chiller/dehydrator dew point temperature too high [1]

Note:
1 – Depending on the air plant configuration, a "too high" dew point temperature is defined as greater than 50 or 65 degrees.

Application of Expert FMEA

Based on the literature, it was determined that a panel of experts would be necessary to develop a holistic perspective on the behavior of the system. The approach to the elicitation of the experts' judgment would be a Delphi Methodology, capturing the underlying theme of the literature on expert elicitation as supported by Baecher (2002). Structure for the process is provided through the use of FMEA worksheet provided to the experts. The approach to the elicitation is as follows:

1. Develop a FMEA worksheet based on the theoretical failure modes. The worksheet allows the expert to assert his opinion on the three components of the RPN has detailed in the conceptual model based on a nominal scale.
2. Select the panel of experts displaying a broad spectrum of expertise on the LP-MPAC system.
3. Discuss the theoretical failure modes with the experts to determine the applicability for use in the effort. Take inputs from the experts as to specific line codes for removal from the study and where additional codes must be included.
4. Provide training to the experts on how to best approach the quantification of their beliefs on the FMEA worksheet. An example is provided for discussion, and questions regarding the scales, provided to guide their opinions, are addressed.
5. The experts are then asked to record their opinions over the next week individually on the work sheet provided.
6. The expert worksheets are collected. The mean numeric value of the expert response to each failure mode is then recorded on a worksheet and provided to the group of experts.
7. The experts are asked to compare the mean response to each failure mode RPN component to their individual response. Discussion among the experts is now encouraged and is guided through the facilitator until a consensus is reached on the each response. The consensus is recorded as a discrete value.
8. The documented consensus is then distributed to each of the experts for final review.

FMEA Worksheet

The FMEA worksheet was developed based on the System Functional Failure Definitions and the Theoretical Failure Modes developed by the COMNAVSURFLANT effort. A portion of the FMEA worksheet is presented (Figure 13) as an example of the basic layout of the worksheet developed for use.

Function	Failure Mode	Potential cause of failure	Severity	Impact of Failure	Occurrence	Probability of Occurrence	Repair	Probability of Repair	RPN
Air Compression	No Pressure, No Capacity	**1A1 Motor failure**							
		1A2 Shutdown switch failed in shutdown position							
		1A3 Motor controller failure							

Figure 13, FMEA Worksheet Example

Selection of Experts

Experts were requested from, and provided by, the office of the Commander Naval Surface Fleet Atlantic (COMNAVSURFLANT). Experts provided were selected from FTSCLANT (Fleet Technical Support Center Atlantic), AMSEC LLC, SUPSHIP (Supervisor of Ships) Portsmouth, and COMNAVSURFLANT for participation in the process. While the experts supplied from the differing organizations had some technical expertise in the LP-MPAC system, the FTSCLANT representatives were the absolute technical experts on the LP-MPAC system itself. FTSCLANT representatives are certified to assess the system and provide technical support to the fleet. The remaining members of the expert panel were not as knowledgeable in the technical areas of the system, their expertise in the maintenance capabilities of the system operators and the area of mission effect is recognized as necessary to provide breadth to the consensus model.

Each member of the panel was asked to complete a qualifying questionnaire. The questionnaire is supplied in Appendix B, and was used to capture data such as educational training, experience with the system, mission requirements and familiarity with existing maintenance personnel training to document the expert was qualified to be a member of the panel.

Discussion of the System Failure Definition and Theoretical Failure Modes and Expert Training on Scoring the FMEA Categories

Experts on the panel reviewed the theoretical failure modes. Modifications were made to arrive at an agreement on the cause of specific failure modes and the worksheet was revised accordingly. Additionally the experts were given direction on how to complete the FMEA worksheet. Appendix A is an example FMEA worksheet and a group of Tables that provide guidance to the arrival at a nominal scale score to be used when filling out the FMEA worksheet. This information was presented to the expert panel and reviewed to ensure that all experts were in agreement on the scales used to score their opinions.

Compilation of Expert Opinion

Expert FMEA work sheets were collected and compiled. The average scores for each RPN factor was then calculated and provided to the experts. After a lengthy discussion, a consensus was reached and recorded. The FMEA worksheet was then presented to the experts for final review.

Research Methodology Summary

A reductonistic systems model was developed. From that model, and through expert elicitation via a modified FMEA, expert model a holistic perspective of system behavior was modeled through the production of RPNs based on the tightly held knowledge of the experts. The results were then compared to an RPN comparative of historical data and existing maintenance procedural guidelines to test the model developed. The analysis of data and the interpretation of the results will be discussed in the next chapter.

CHAPTER V

RESULTS OF RESEARCH

Introduction

This chapter discusses the assimilation of a panel of experts and compares the consensus of the expert panel in the development of RPNs to the historical RPN comparative. The expert RPN and historical RPN are graphically compared. Additionally nonparametric statistics are used to make inferences about the two RPN types (expert and historical). Observations of each test of the four Platforms: A, B, C, and D are made and presented in this chapter along with test of the three factors comprising the RPN. Finally regression analysis is used to determine subsets exerting the greatest influence in the resultant RPN.

Assimilation of Expert Panel

As stated in the previous chapter, a panel of experts was convened. Experts were selected from FTSCLANT, AMSEC LLC, SUPSHIP Portsmouth, and COMNAVSURFLANT for participation in the process. While the experts supplied from the differing organizations had some technical expertise in the LP-MPAC system, the FTSCLANT representatives were the absolute technical experts on the LP-MPAC system itself. FTSCLANT representatives are certified by COMNAVSURFLANT to assess the system and provide technical support to the fleet. The remaining members of the expert panel were knowledgeable in the technical areas of the system, and held expertise in the maintenance capabilities of the system operators and the area of mission effect is recognized as necessary to provide breadth to the consensus model.

Each member of the panel was asked to complete a qualifying questionnaire. The questionnaire is supplied in Appendix B, and was used to capture data such as educational training, experience with the system, mission requirements and familiarity with existing maintenance personnel training to document the expert was qualified to be a member of the panel. The rejection threshold for this effort was less than 5 years experience in the area of expertise assigned. This was confirmed by COMNAVSURFLANT for the experts provided; no experts were rejected based on this criteria from those provided by COMNAVSURFLANT.

Expert	Education and Training	Group Affiliation	Area of Expertise
A	High School 20+ yrs experience with LPAC/MPAC System	FTSCLANT	Maintenance and Repair of LPAC/MPAC Systems
B	BSME MS	SUPSHIP	Maintenance Policy
C	BSME	SUPSHIP	Maintenance Policy
D	BSME	COMNAVSURFLANT	Process Engineering. Maintenance Strategy
E	BSME	SUPSHIP	General Engineering
F	BSME BS (Mathematics) 42+ years Shipbuilding Design and Repair	AMSEC	Assessment Analyst
G	20+year Experience OEM Training on LPAC/MPAC Platforms BSMET	FTSCLANT	Maintenance and Repair of LPAC/MPAC Systems
H	BSEM, MEM 10+ Years Experience LPAC/MPAC Maintenance and Repair	FTSCLANT	Supervisor of LPAC/MPAC Maintenance Atlantic Fleet

Table 7, Expert demographics.

Experts on the panel reviewed the theoretical failure modes. Modifications were made to arrive at an agreement on the cause of specific failure modes and the worksheet was revised accordingly. Additionally the experts were given direction on how to complete the FMEA worksheet. Appendix A is an example FMEA worksheet and a group of tables that provide guidance to the arrival at a nominal scale score to be used when filling out the FMEA worksheet. This information was presented to the expert panel and reviewed to ensure that all experts were in agreement on the scales used to score their opinions.

Results

Data was compiled and reviewed. The study addressed 113 different ships. Among the 113 ships there were 305 air compressors distributed among the LP-MPAC systems. Two distinct configuration types were observed in the LP-MPAC systems studied based on the type of compressor: RHS (Rotary Helical Screw) and RCP (Reciprocating). RHS type configuration additionally decomposed into two classes: RHS-S (Rotary Helical Screw – Star) and RHS-N (Rotary Helical Screw – NAXI). RHS compressors were used only on LPAC systems. RCP compressors were used on both LPAC and MPAC systems. Additionally the systems understudy were grouped according to the number of air compressors the system contained. To test the model only reciprocating compressors were used, as they were of consistent class and type. These were then grouped into the four platforms for comparison based on system similarity.

Comparison of RPNE to RPNH

Based on system configuration, between 77 and 87 distinct failure modes were addressed in each platform. Once the RPNs were compiled from the experts FMEA, the data (in the form of the Expert RPN) was weighed against the Historical RPN comparative developed for the test of the hypothesis presented in the previous chapter as Hypothesis 1. Initially data was graphed to visualize the differences in the Expert RPN and the Historical RPN comparative. An example of the graphical representation is shown in figures 14-17.

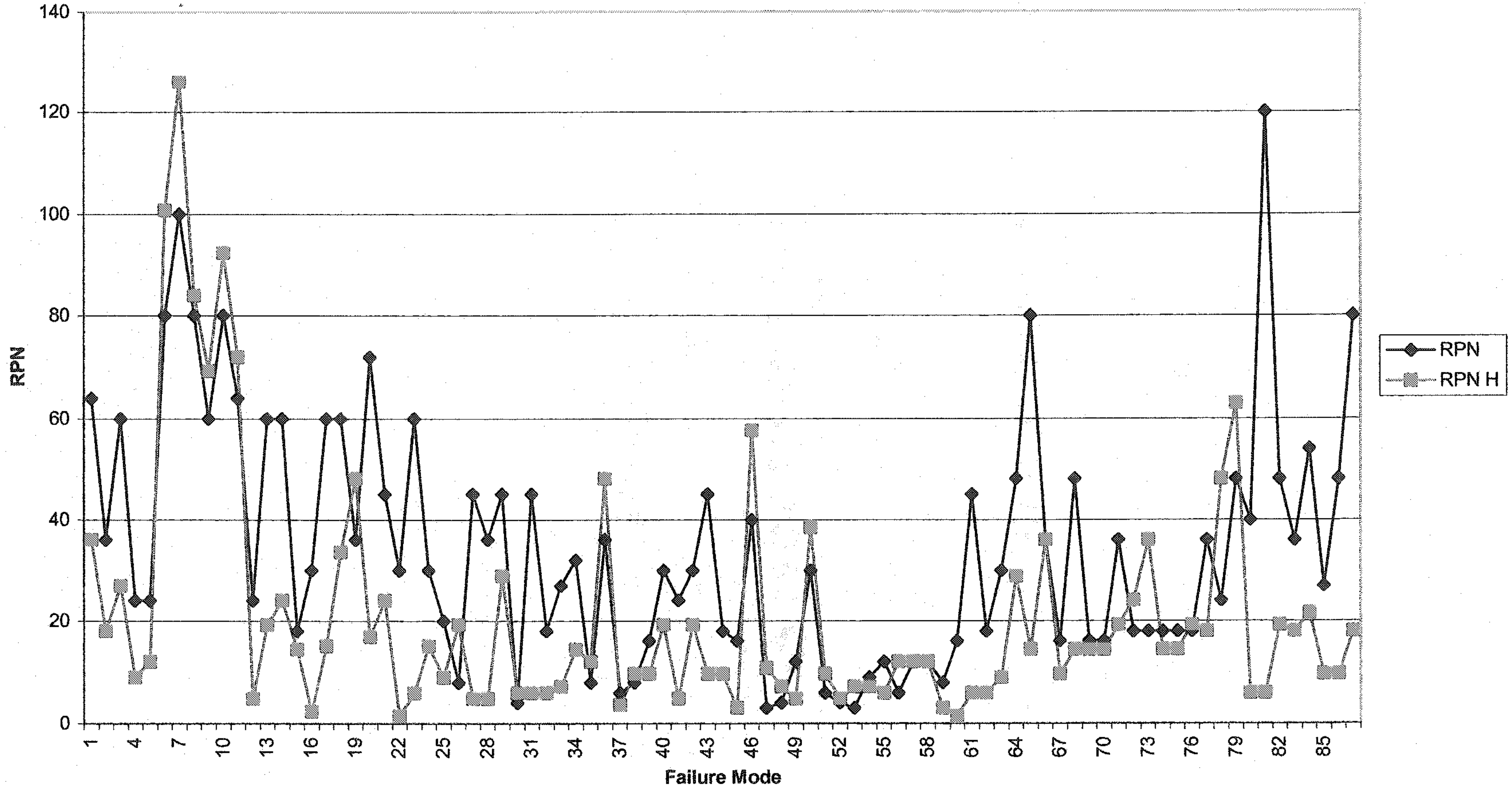


Figure 14, Comparison of RPN E and RPN H, Platform A.

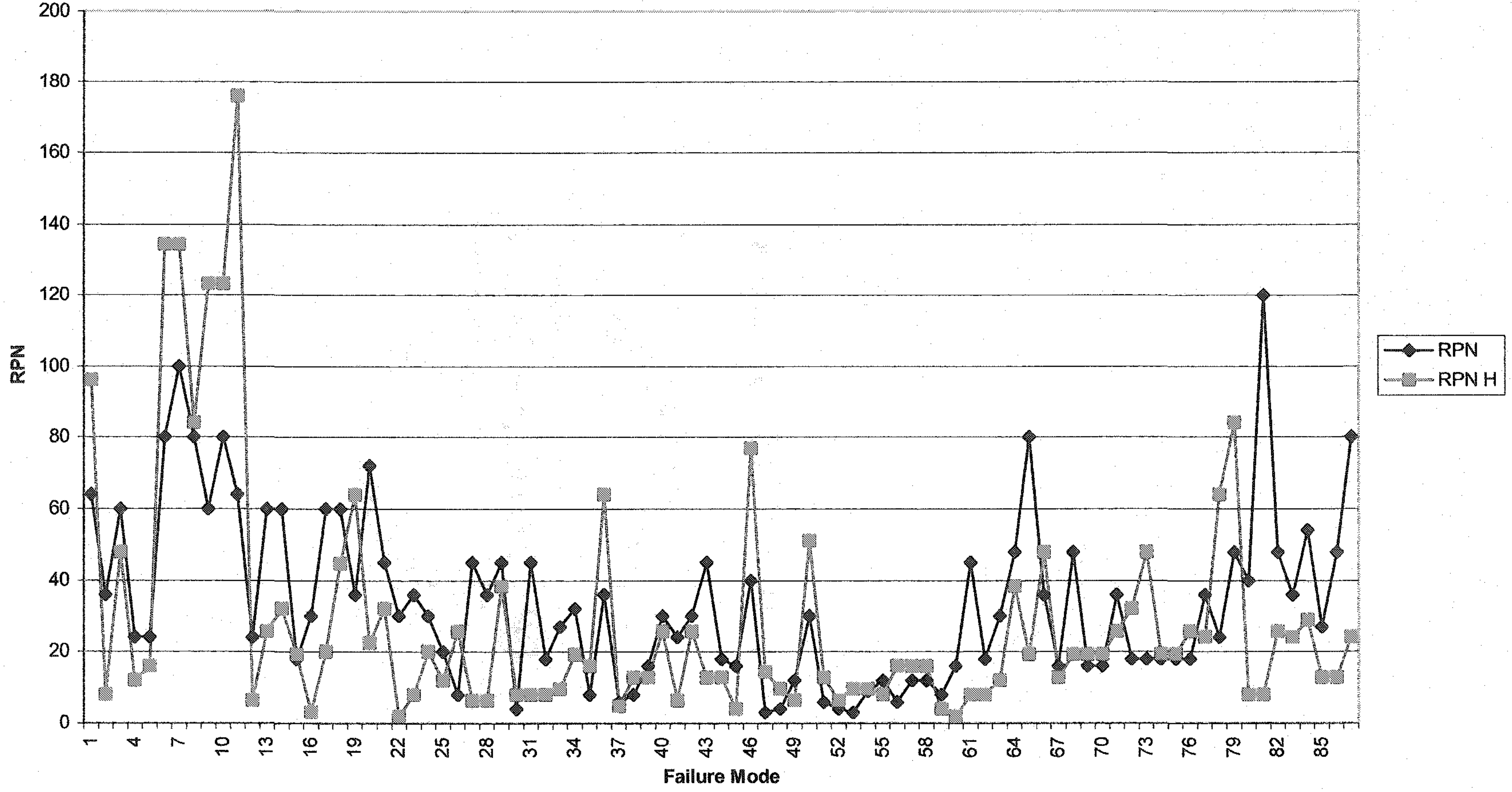


Figure 15, Comparison of RPN E and RPN H, Platform B.

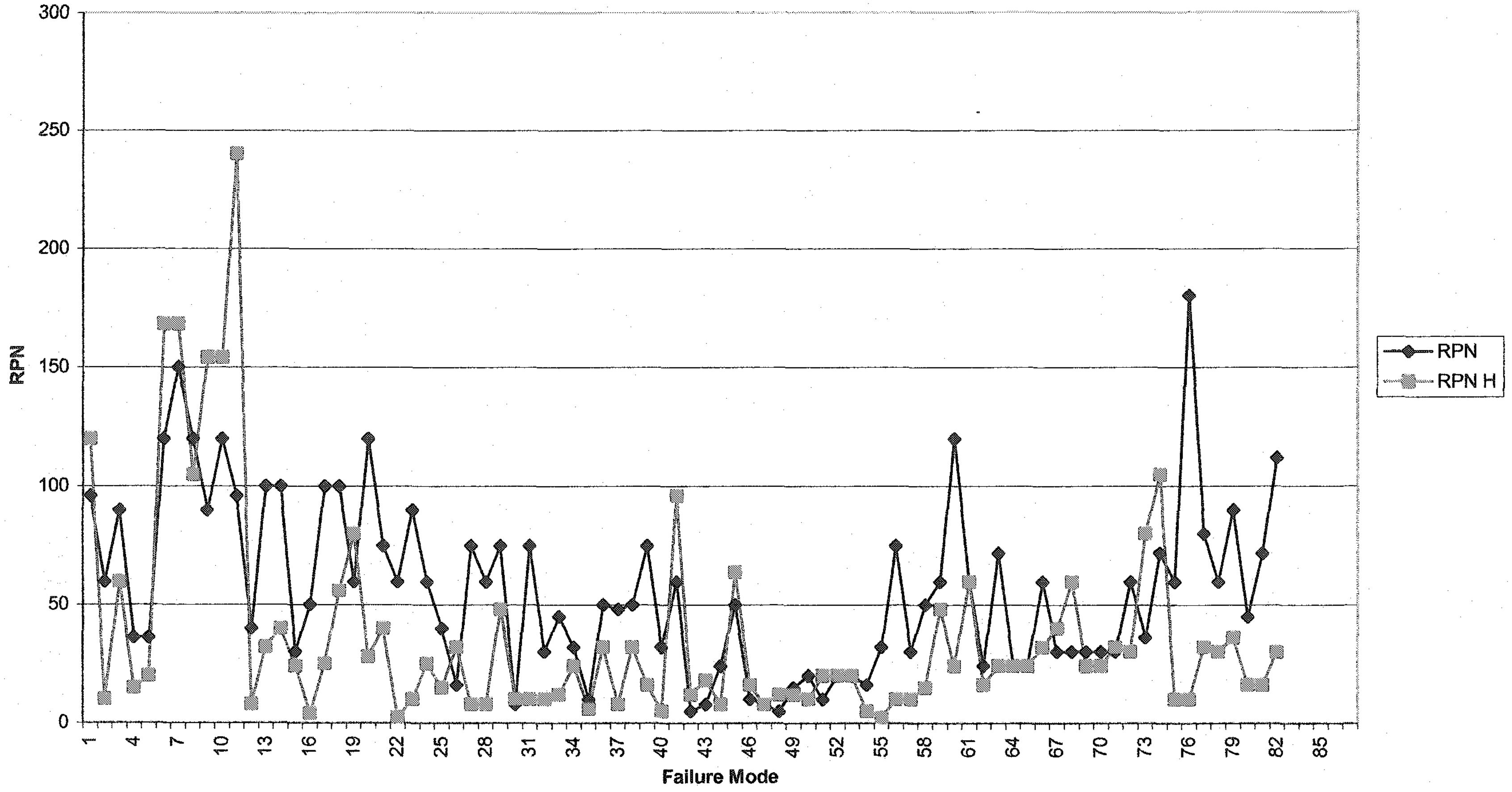


Figure 16, Comparison of RPN E and RPN H, Platform C.

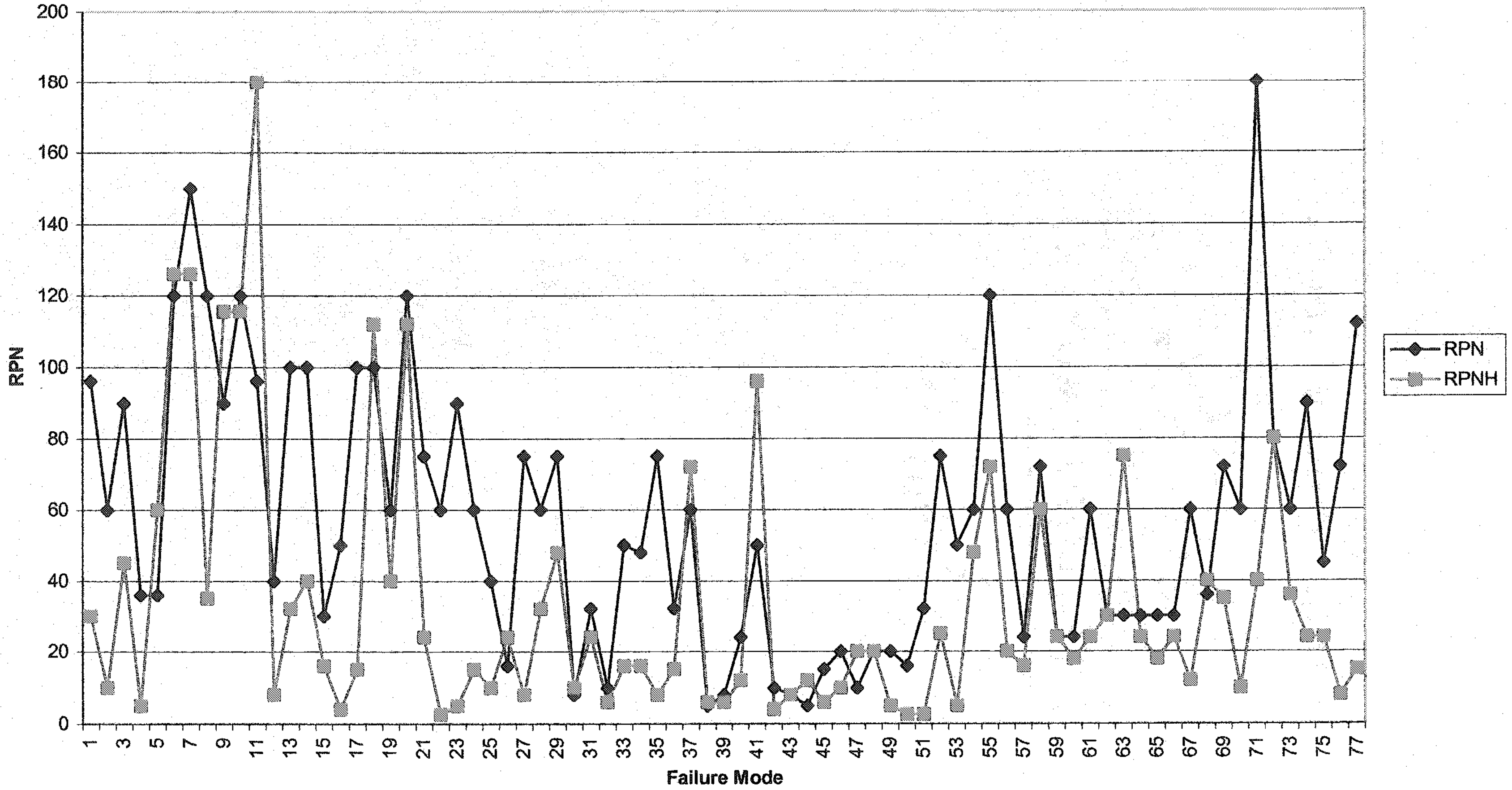
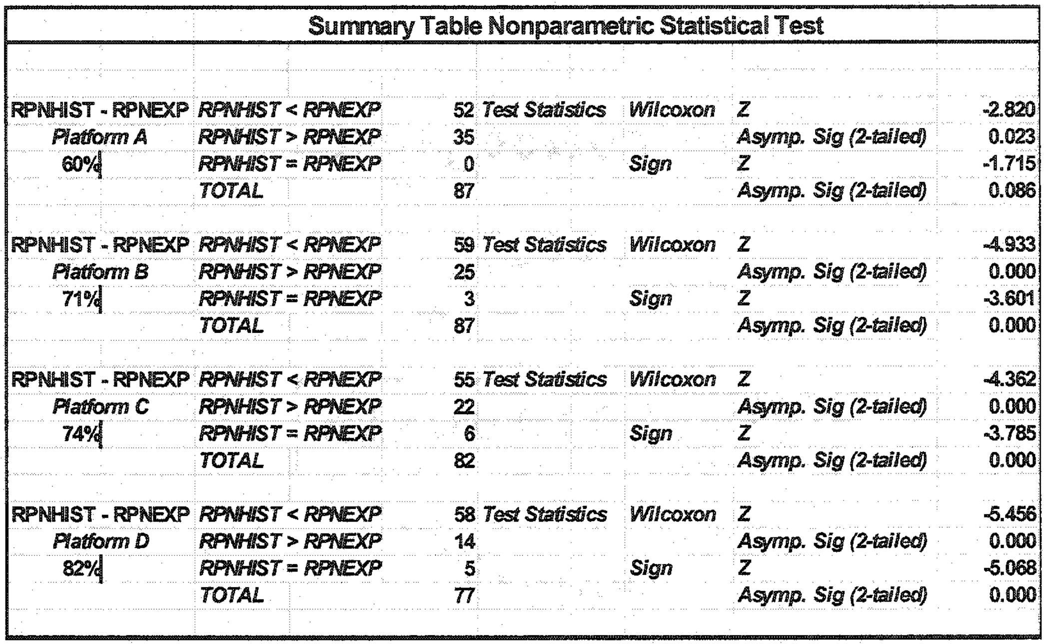


Figure 17, Comparison of RPN E and RPN H, Platform D.

While a graphical approach showed that the Expert RPN trended as expected, further statistical tests were deemed necessary. A Wilcoxon sign rank sum test for matched pairs was used to evaluate the data. The selection of use for the non-parametric statistical analysis was based on the non-normality of the expert responses. SPSS was used to perform the analysis.



Summary Table Nonparametric Statistical Test

RPNHIST - RPNEXP	*RPNHIST < RPNEXP*	52	*Test Statistics*	*Wilcoxon*	*Z*	-2.820
Platform A	*RPNHIST > RPNEXP*	35			*Asymp. Sig (2-tailed)*	0.023
60%	*RPNHIST = RPNEXP*	0		*Sign*	*Z*	-1.715
	TOTAL	87			*Asymp. Sig (2-tailed)*	0.086
RPNHIST - RPNEXP	*RPNHIST < RPNEXP*	59	*Test Statistics*	*Wilcoxon*	*Z*	-4.933
Platform B	*RPNHIST > RPNEXP*	25			*Asymp. Sig (2-tailed)*	0.000
71%	*RPNHIST = RPNEXP*	3		*Sign*	*Z*	-3.601
	TOTAL	87			*Asymp. Sig (2-tailed)*	0.000
RPNHIST - RPNEXP	*RPNHIST < RPNEXP*	55	*Test Statistics*	*Wilcoxon*	*Z*	-4.362
Platform C	*RPNHIST > RPNEXP*	22			*Asymp. Sig (2-tailed)*	0.000
74%	*RPNHIST = RPNEXP*	6		*Sign*	*Z*	-3.785
	TOTAL	82			*Asymp. Sig (2-tailed)*	0.000
RPNHIST - RPNEXP	*RPNHIST < RPNEXP*	58	*Test Statistics*	*Wilcoxon*	*Z*	-5.456
Platform D	*RPNHIST > RPNEXP*	14			*Asymp. Sig (2-tailed)*	0.000
82%	*RPNHIST = RPNEXP*	5		*Sign*	*Z*	-5.068
	TOTAL	77			*Asymp. Sig (2-tailed)*	0.000

Table 8, Summary of Nonparametric Statistical Test, Platforms A-D.

Observations

It is noted that the Expert RPN was equal too or exceeded the Historical RPN comparative 60% of the time in Platform A, 71% of the time in Platform B, 74% of the time in Platform C, and 82% of the time in Platform D. While the percentages are not very high, the significance of the differences do indicate that the RPNE is greater than or equal to the RPNH on both the Wilcoxon and Sign tests. Consequently the analysis supports hypothesis 1 made in the research. However, further review of the data was deemed necessary to explain the lack of the expert RPN exceeding the Historical RPN by a larger percentage.

Comparison of Factors in RPN Model

Initially, the each component of the Expert RPN was compared to the corresponding comparative Historical RPN component to test hypotheses 2, 3, and 4. The comparisons for each platform are presented graphically for comparison in figures 18 through 29.

Hypothesis 2

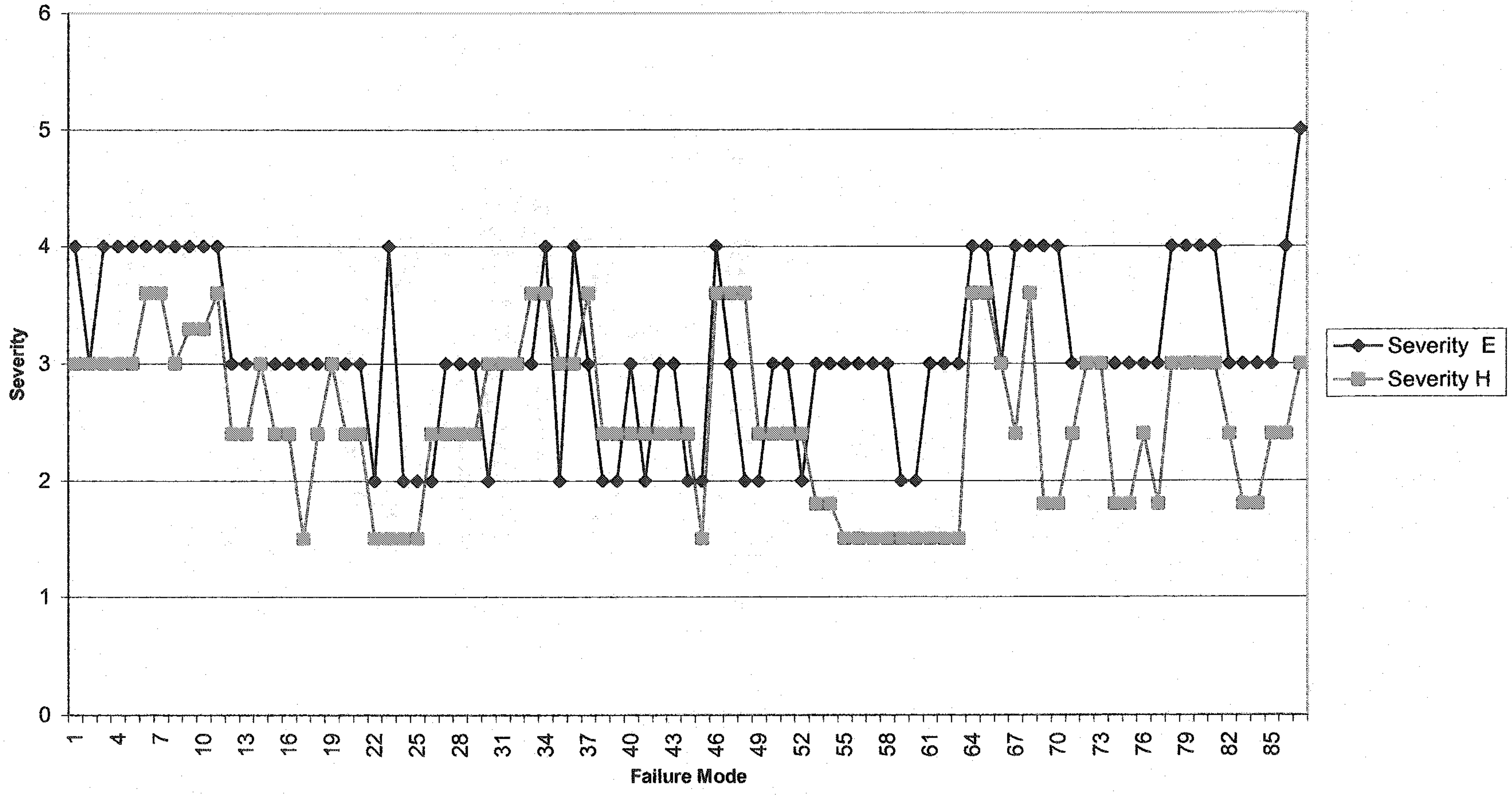


Figure 18, Comparison of Severity E and Severity H, Platform A.

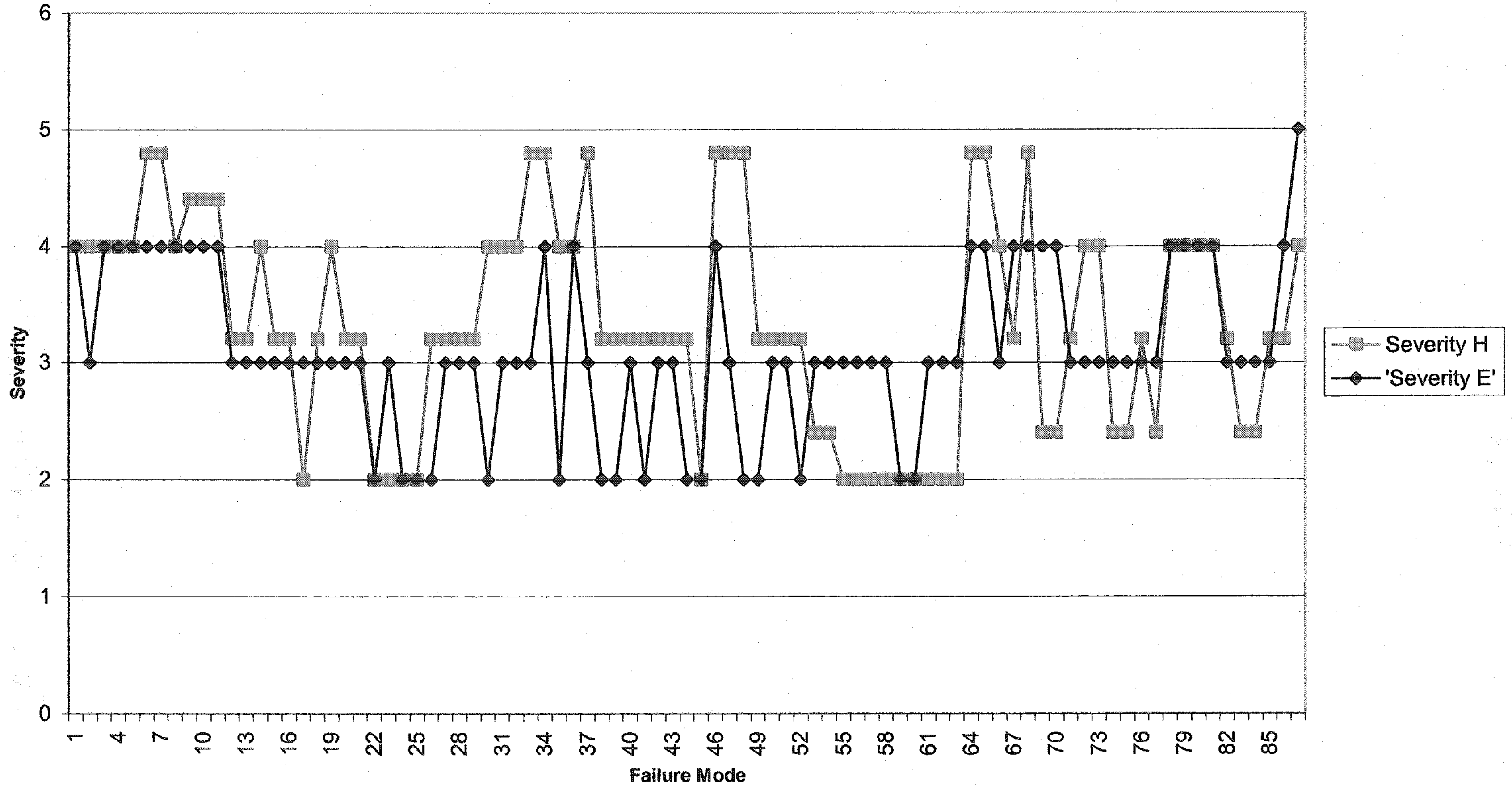


Figure 19, Comparison of Severity E and Severity H, Platform B.

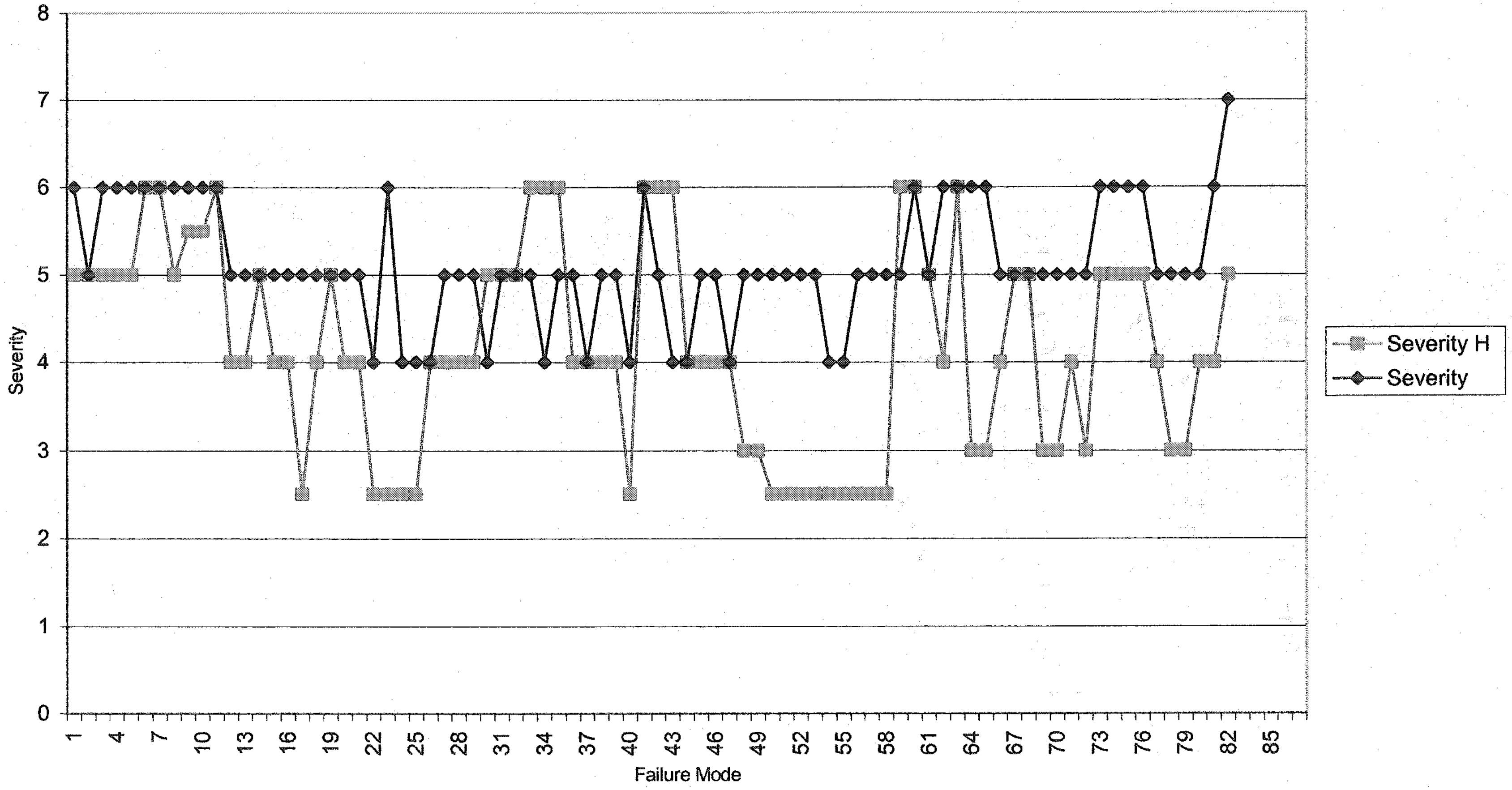


Figure 20, Comparison of Severity E and Severity H, Platform C.

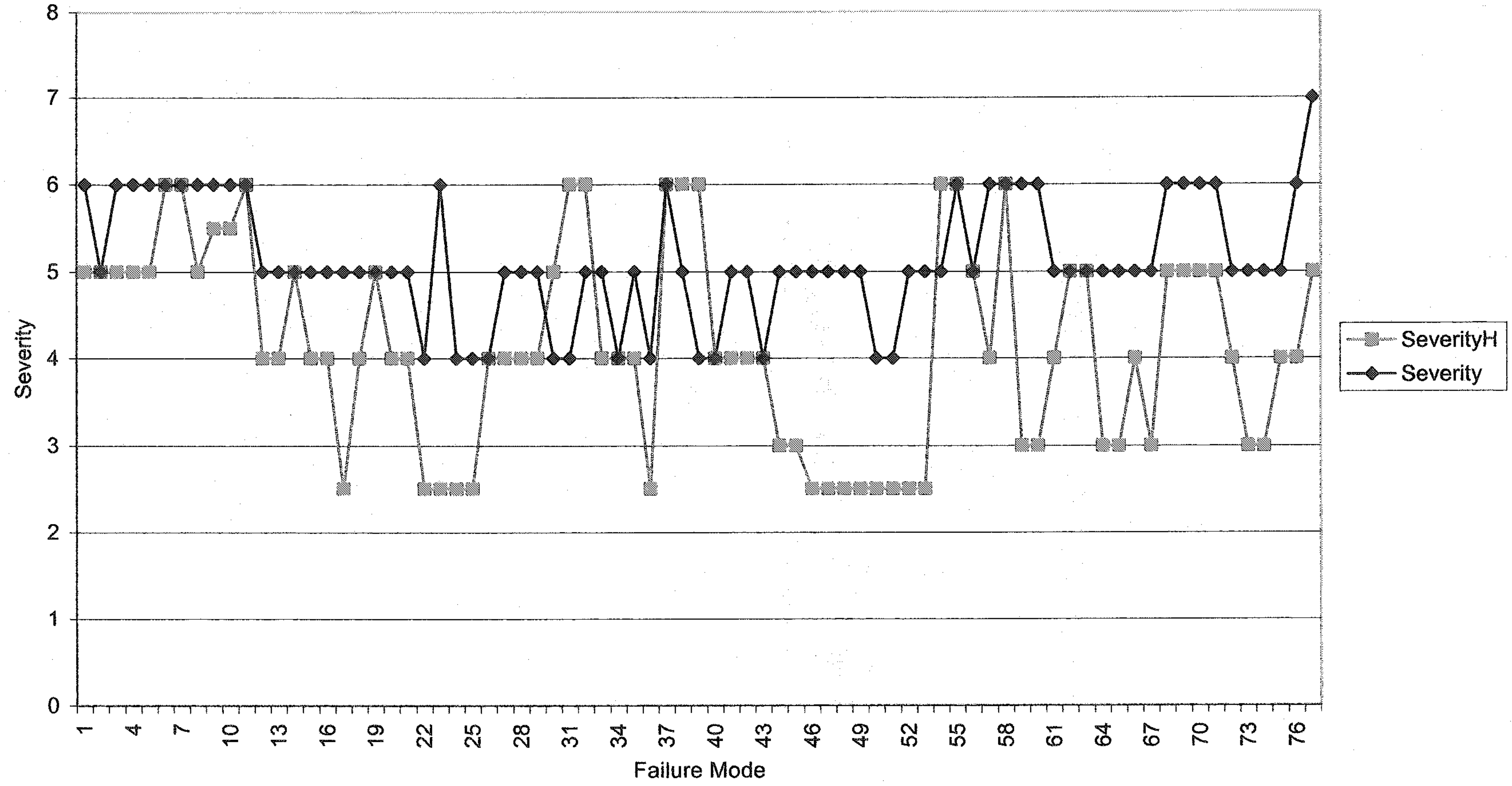


Figure 21, Comparison of Severity E and Severity H, Platform D.

Hypothesis 3

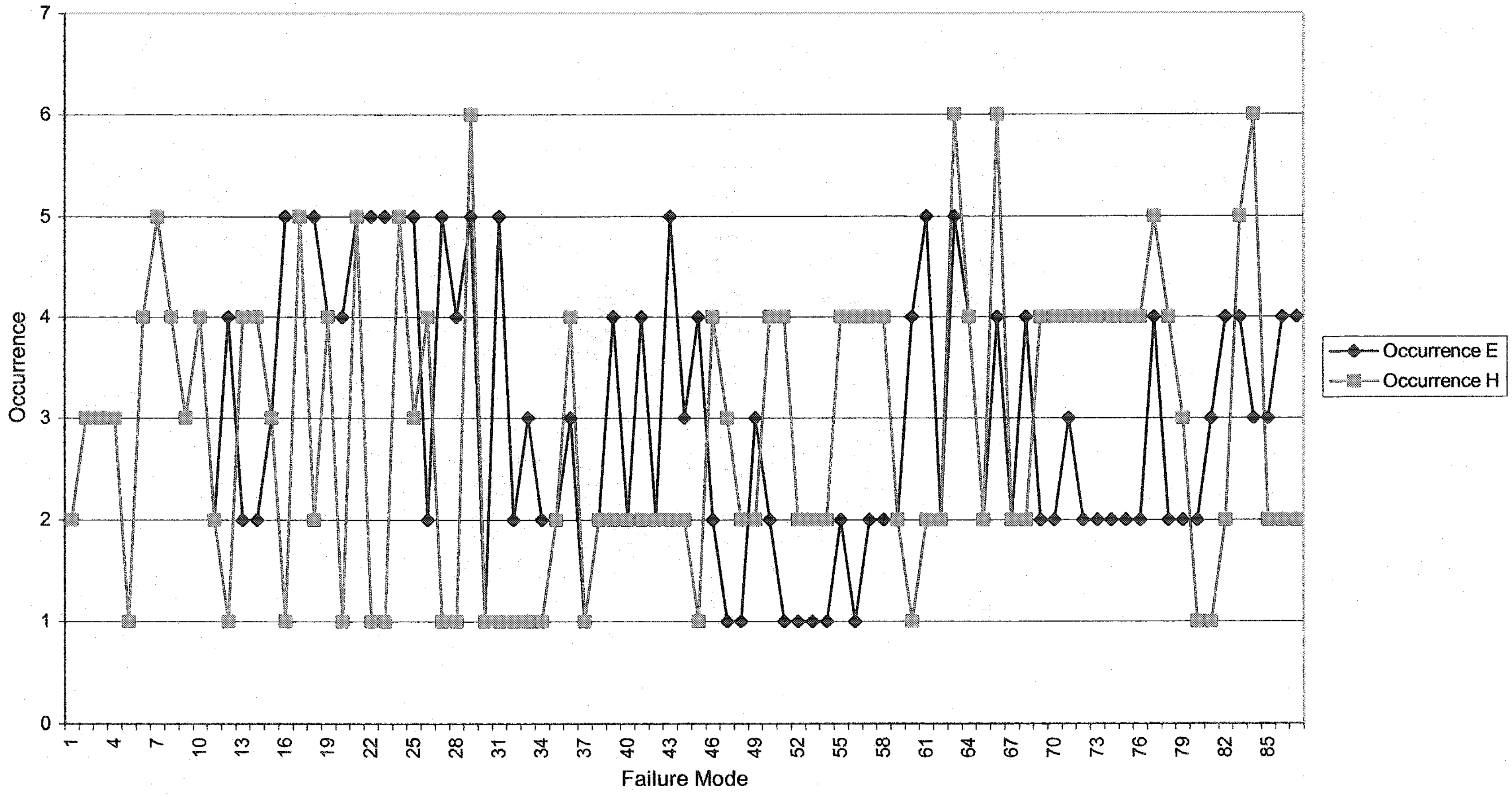


Figure 22, Comparison of Occurrence E and Occurrence H, Platform A.

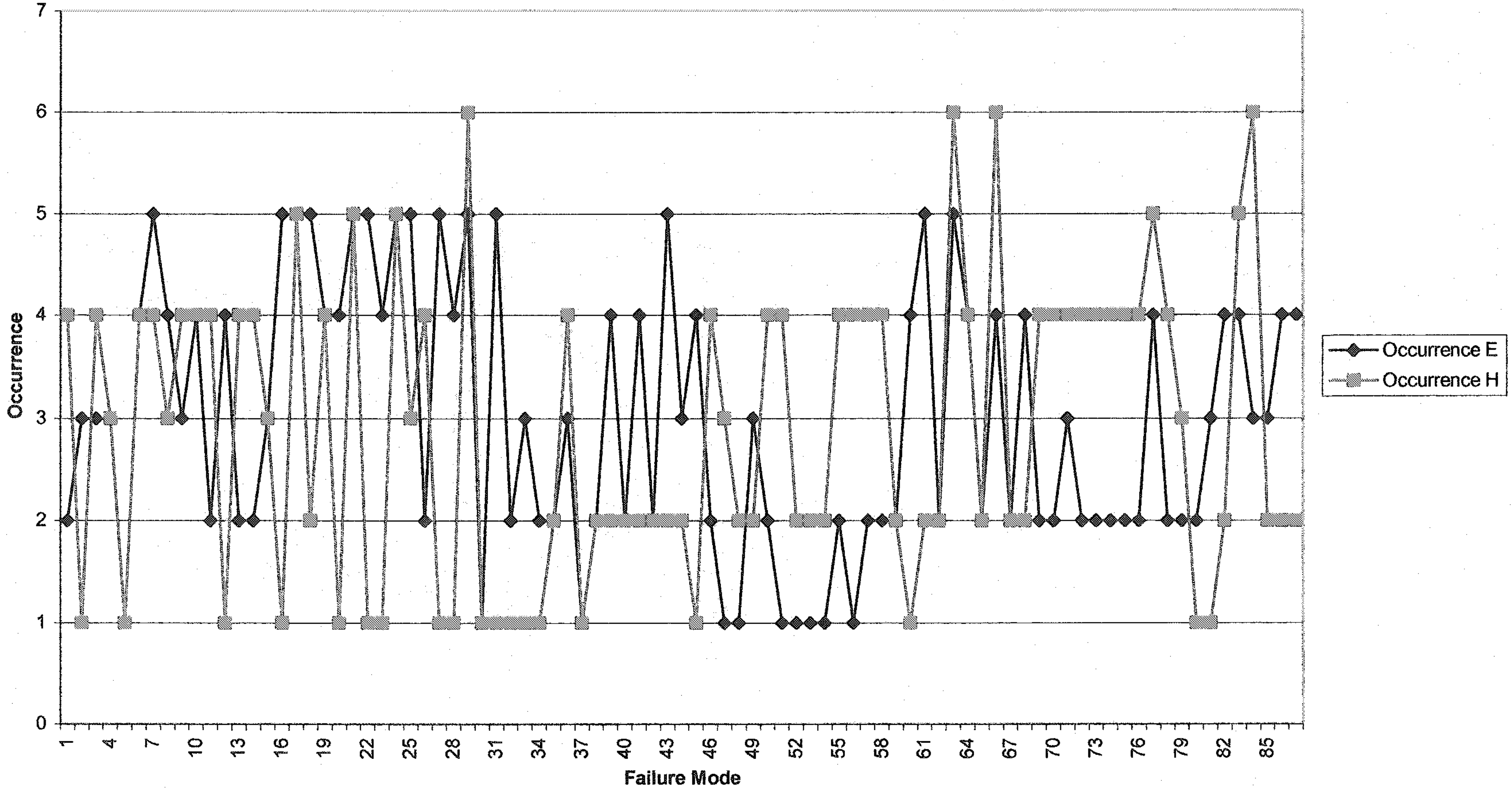


Figure 23, Comparisons of Occurrence E and Occurrence H, Platform B.

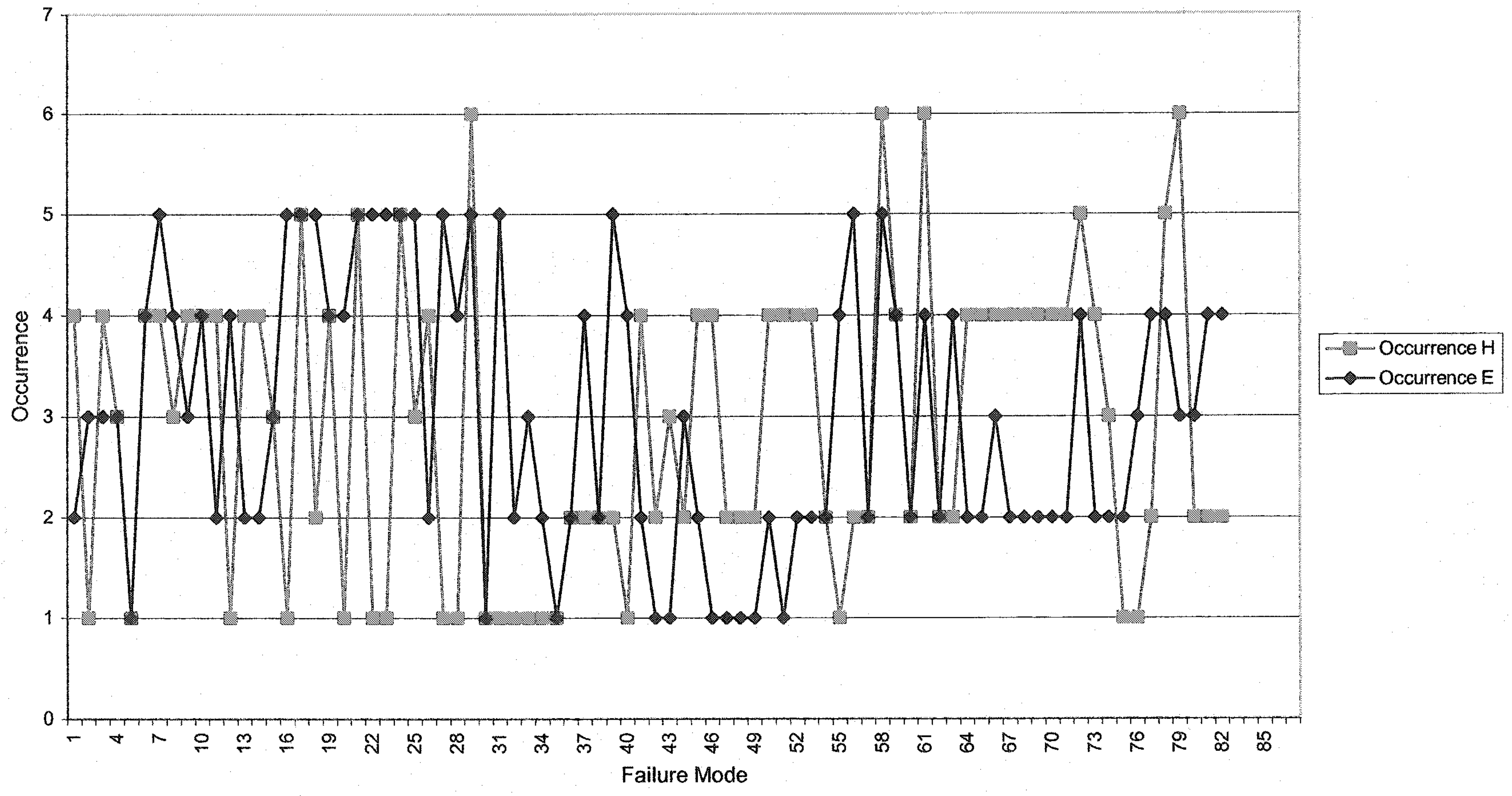


Figure 24, Comparison of Occurrence E and Occurrence H, Platform C.

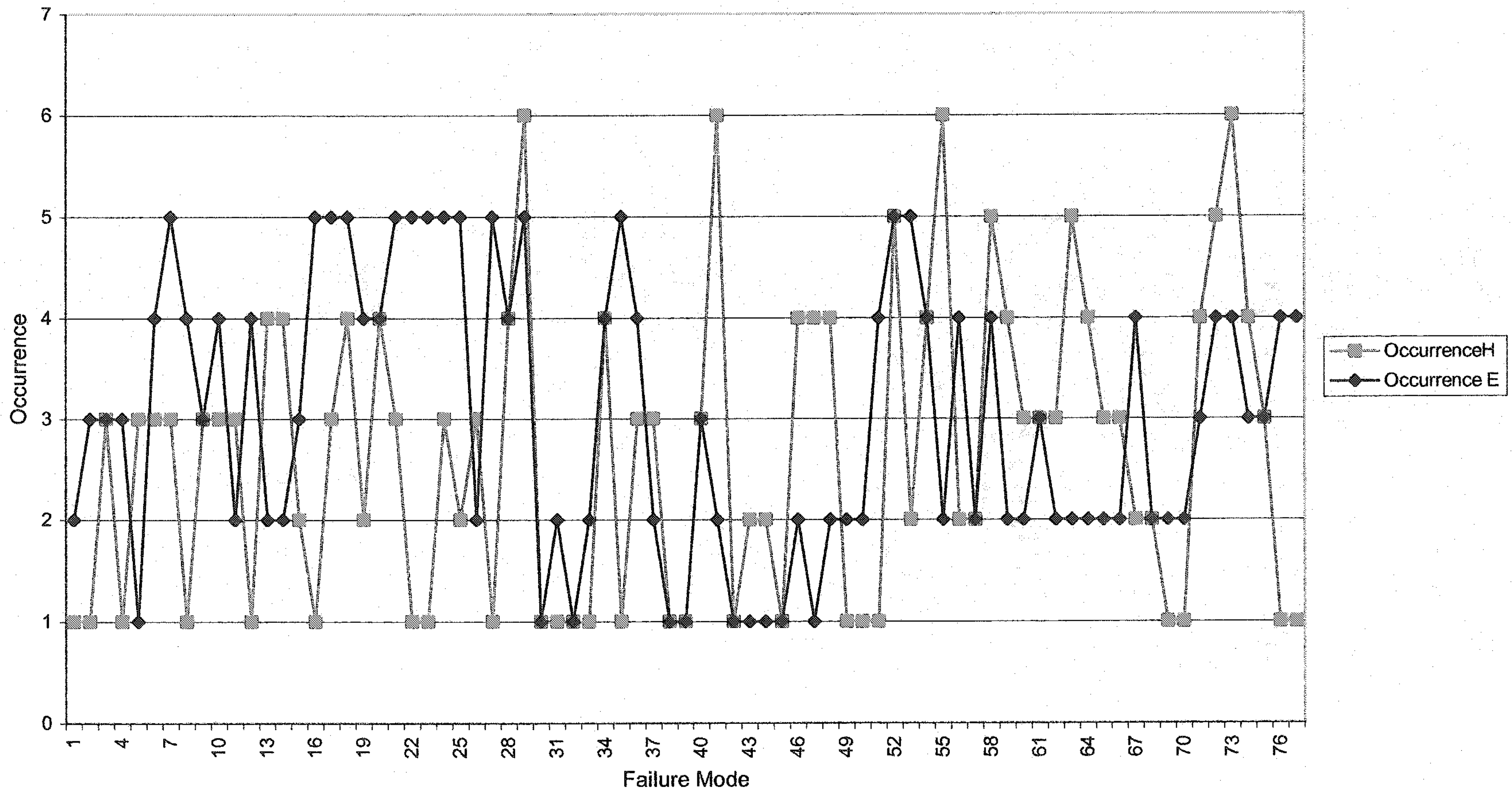


Figure 25, Comparison of Occurrence E and Occurrence H, Platform D.

Hypothesis 4

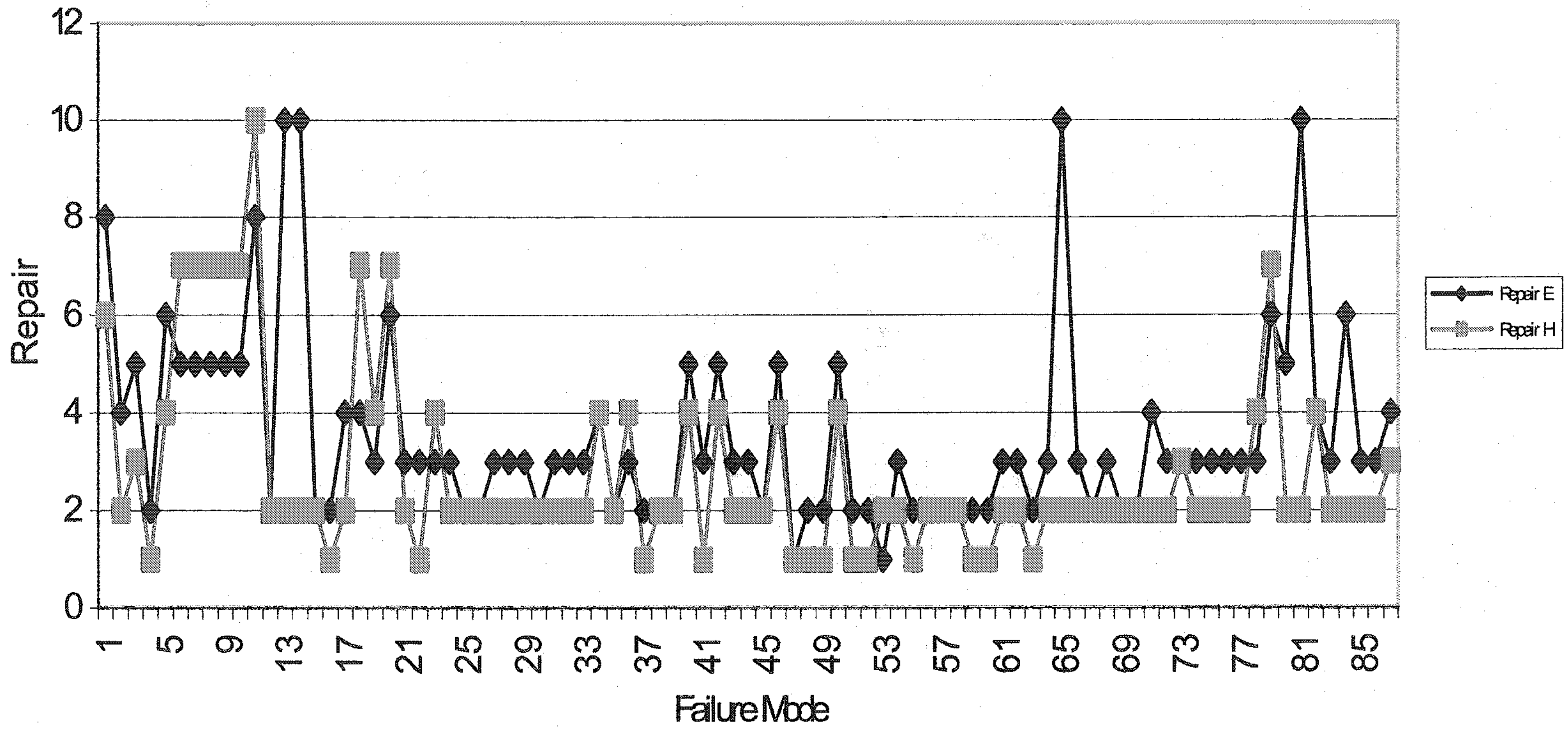


Figure 26, Comparison of Repair E and Repair H, Platform A.

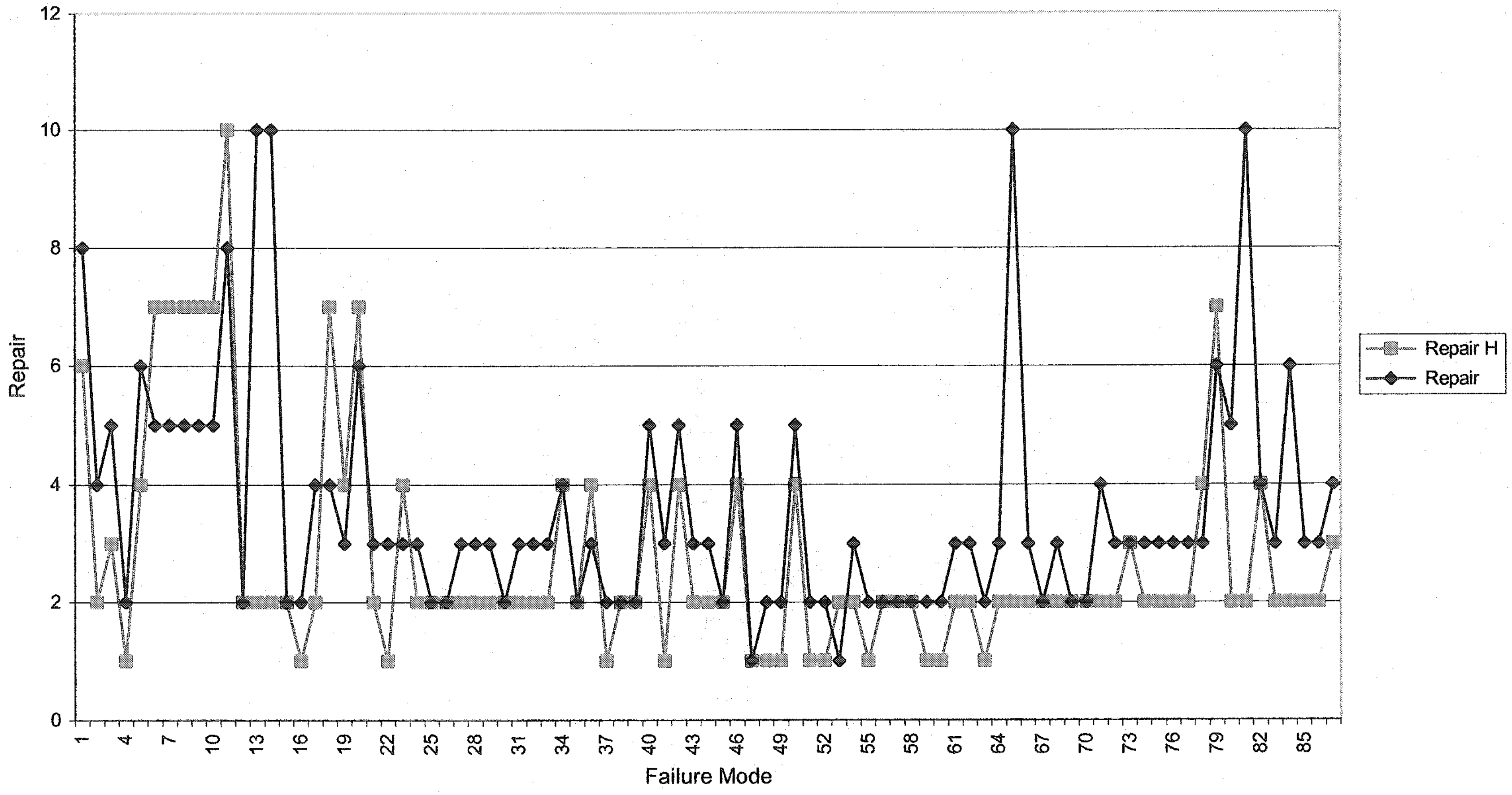


Figure 27, Comparison of Repair E and Repair H, Platform B.

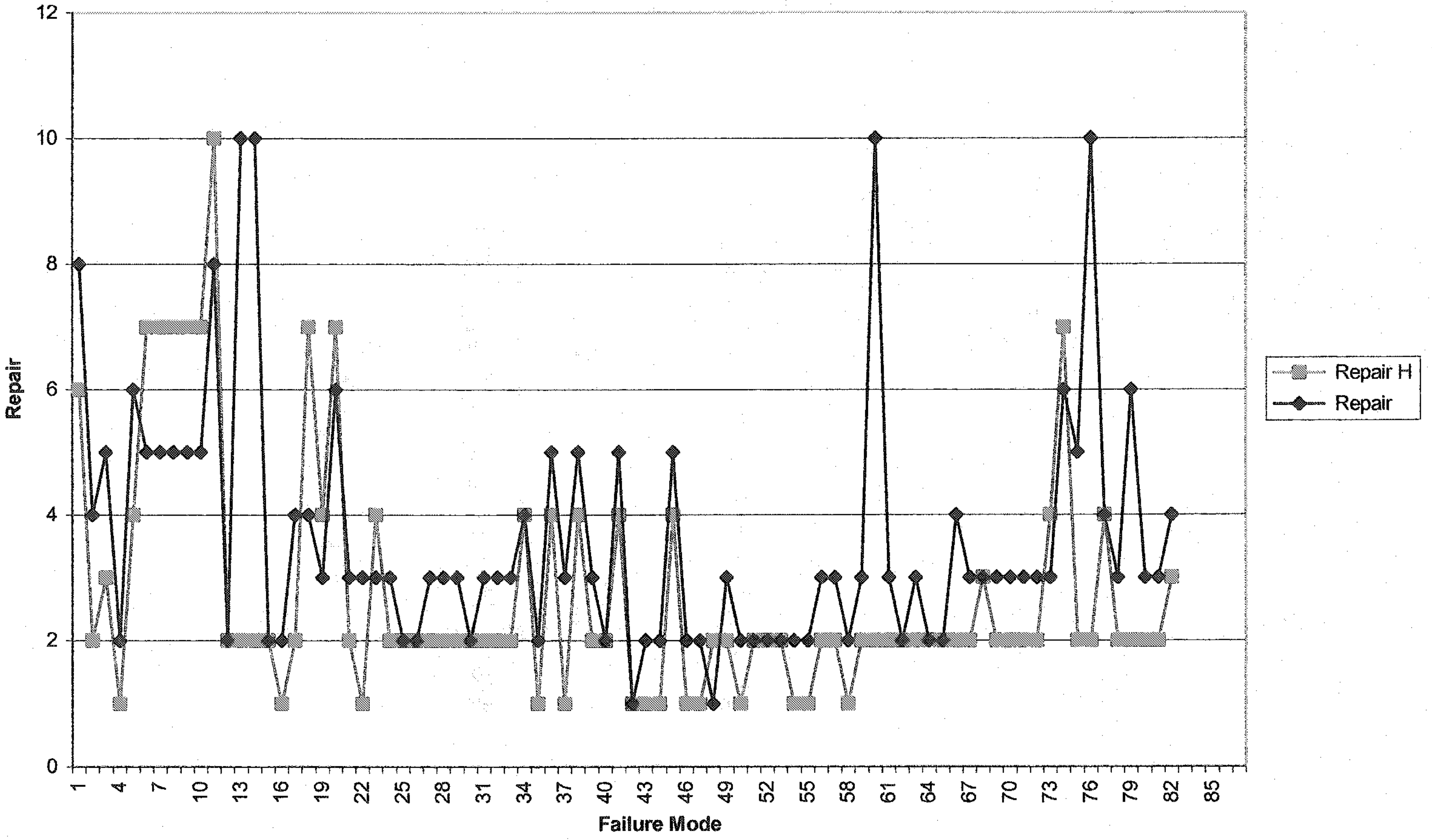


Figure 28, Comparison of Repair E and Repair H, Platform C.

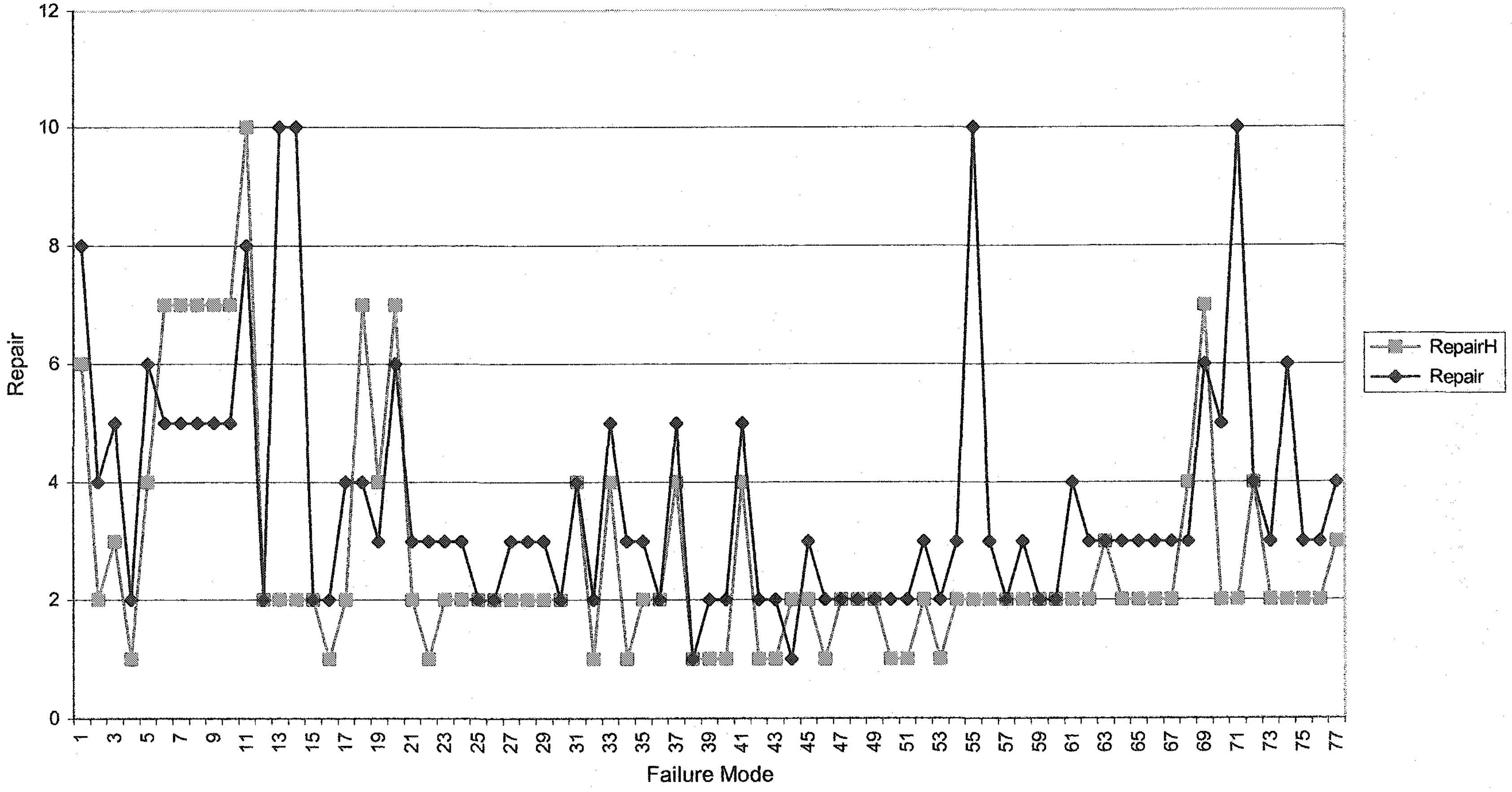


Figure 29, Comparison of Repair E and Repair H, Platform D.

Observations of Results

It was initially apparent that while two components (severity and reparability) (example figures 18-21 and 26-29, respectively) tend to trend comparably with the historical data values in the four platforms, the experts were inconsistent with the historical data on the occurrence of the failures (figures 22-25).

Hypotheses 5, 6 and 7 were tested to determine if a factor or factors exist that contribute to resulting RPN in a greater proportion. The graphical comparisons of the expert versus the historical comparative are presented in figures 30-41.

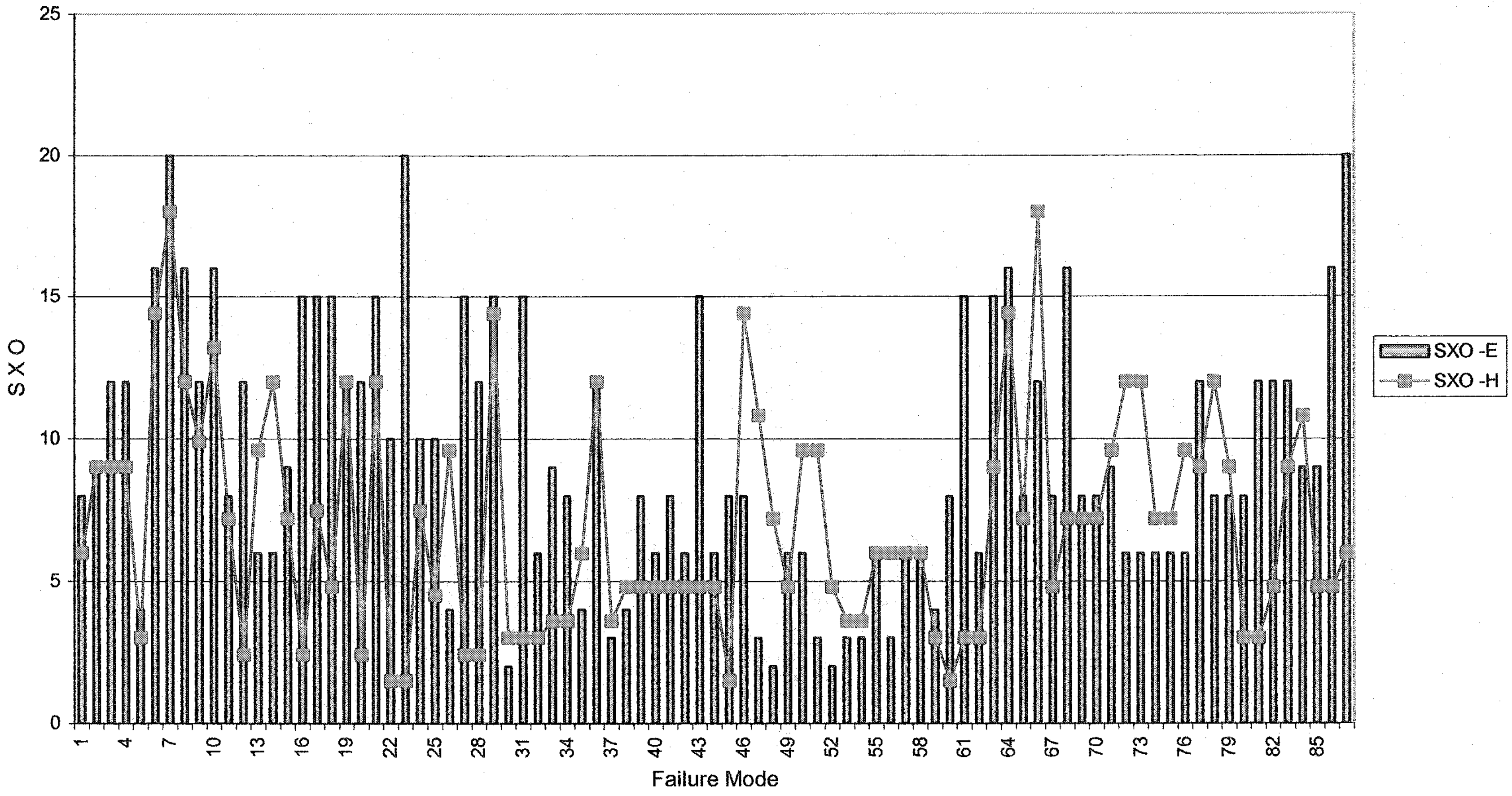


Figure 30, Severity x Occurrence – Platform A.

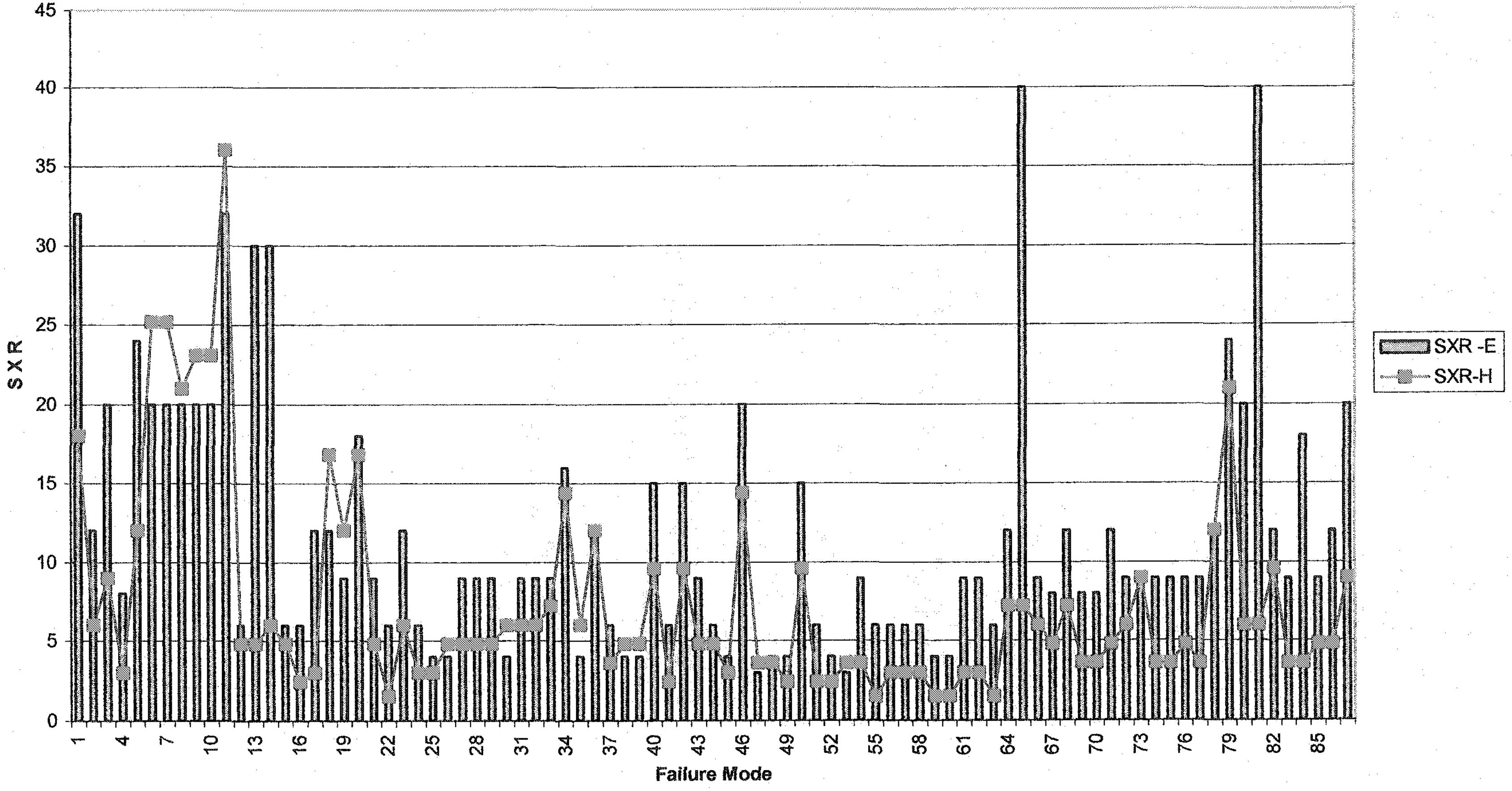


Figure 31, Severity x Repair – Platform A.

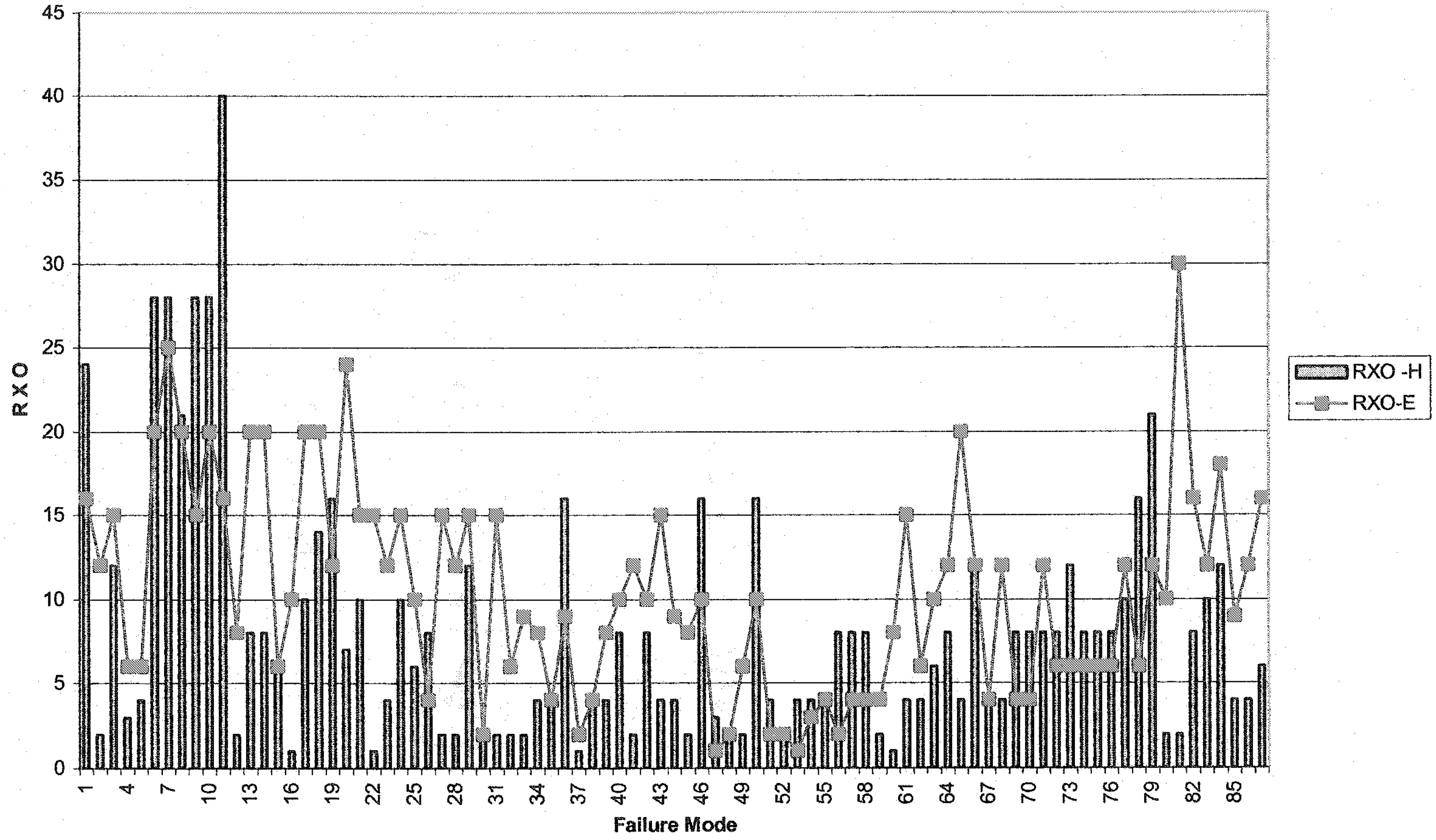


Figure 32, Repair x Occurrence – Platform A.

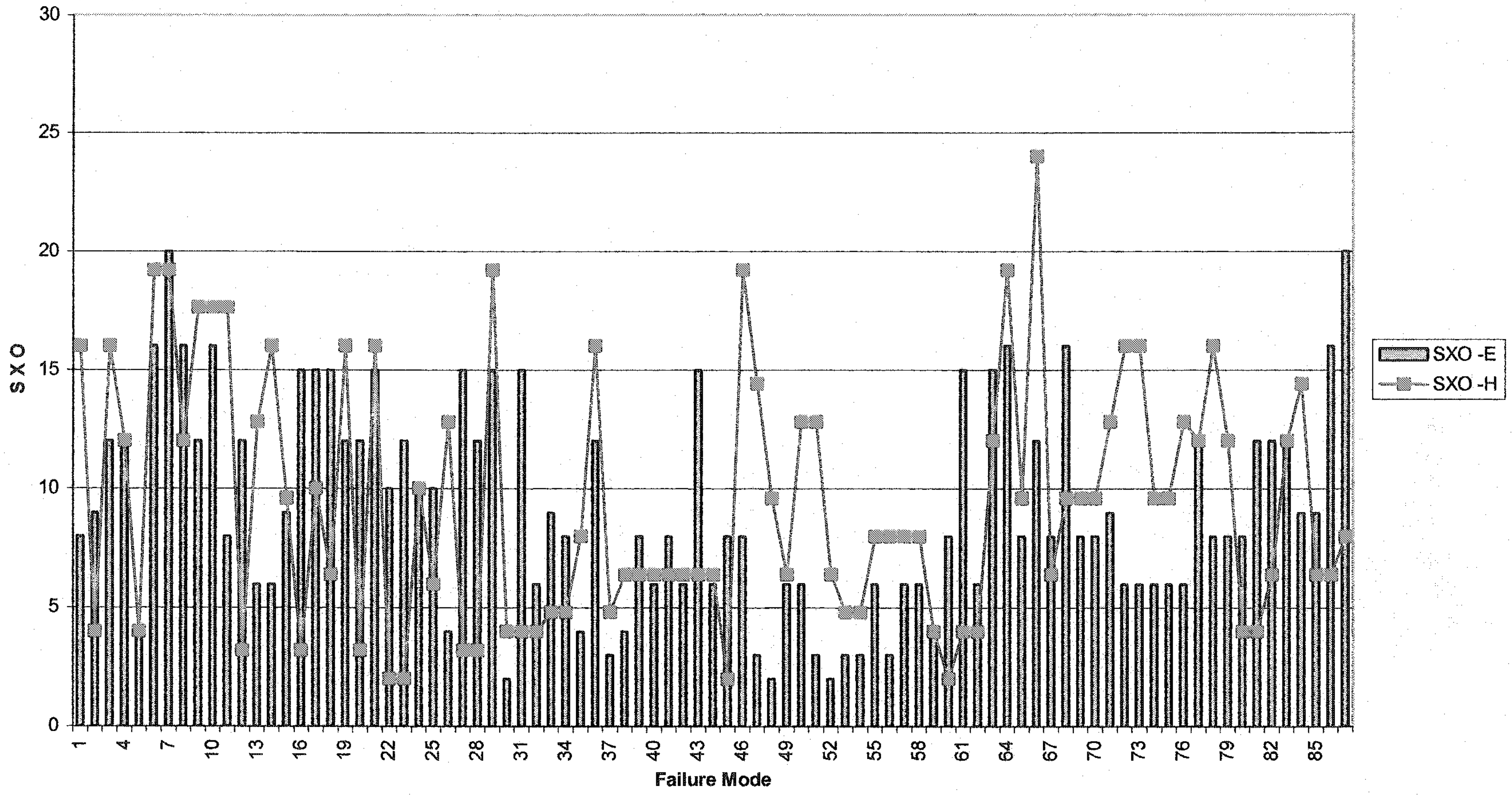


Figure 33, Severity x Occurrence – Platform B.

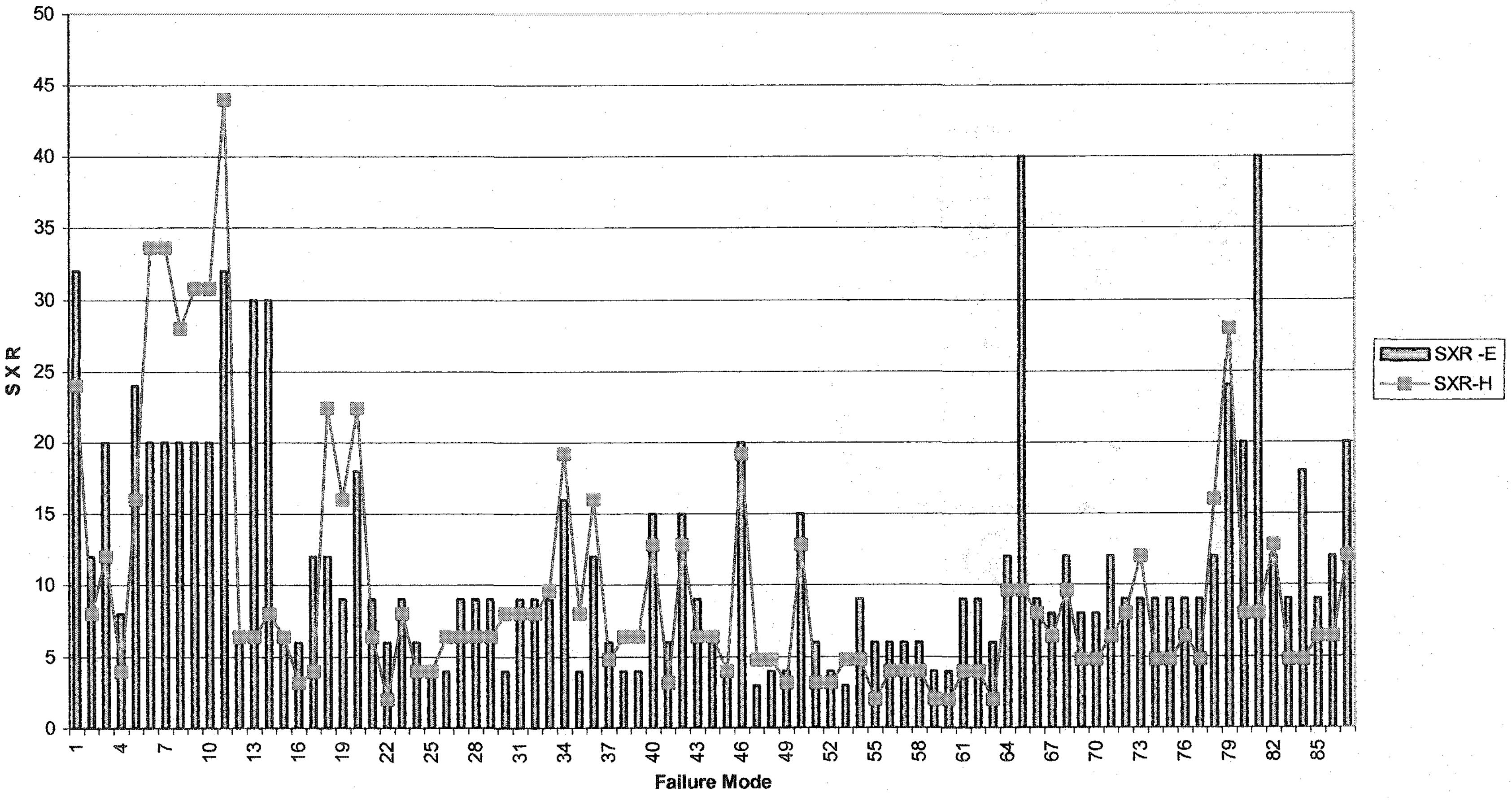


Figure 34, Severity x Repair – Platform B.

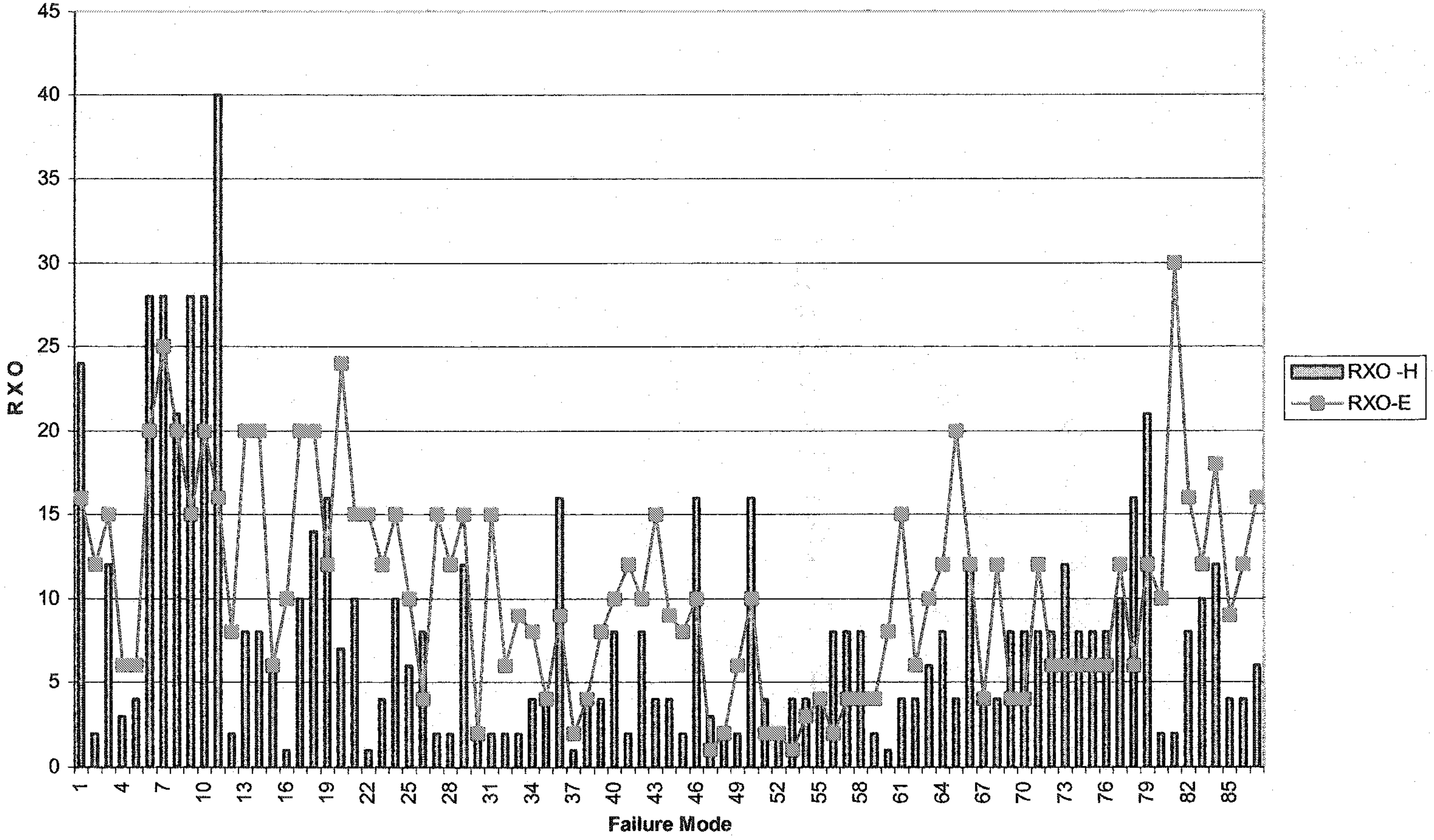


Figure 35, Repair x Occurrence – Platform B.

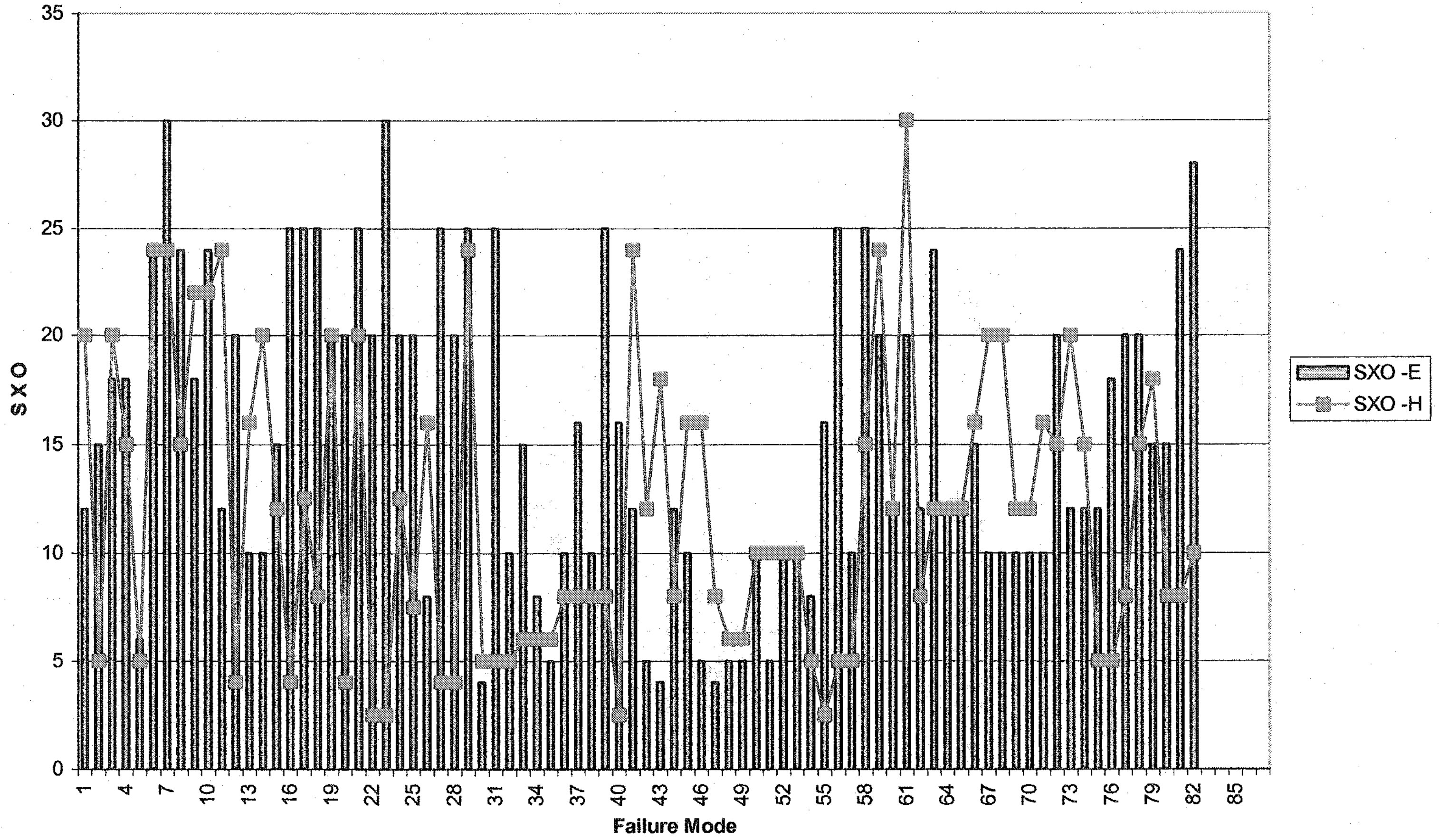


Figure 36, Severity x Occurrence – Platform C.

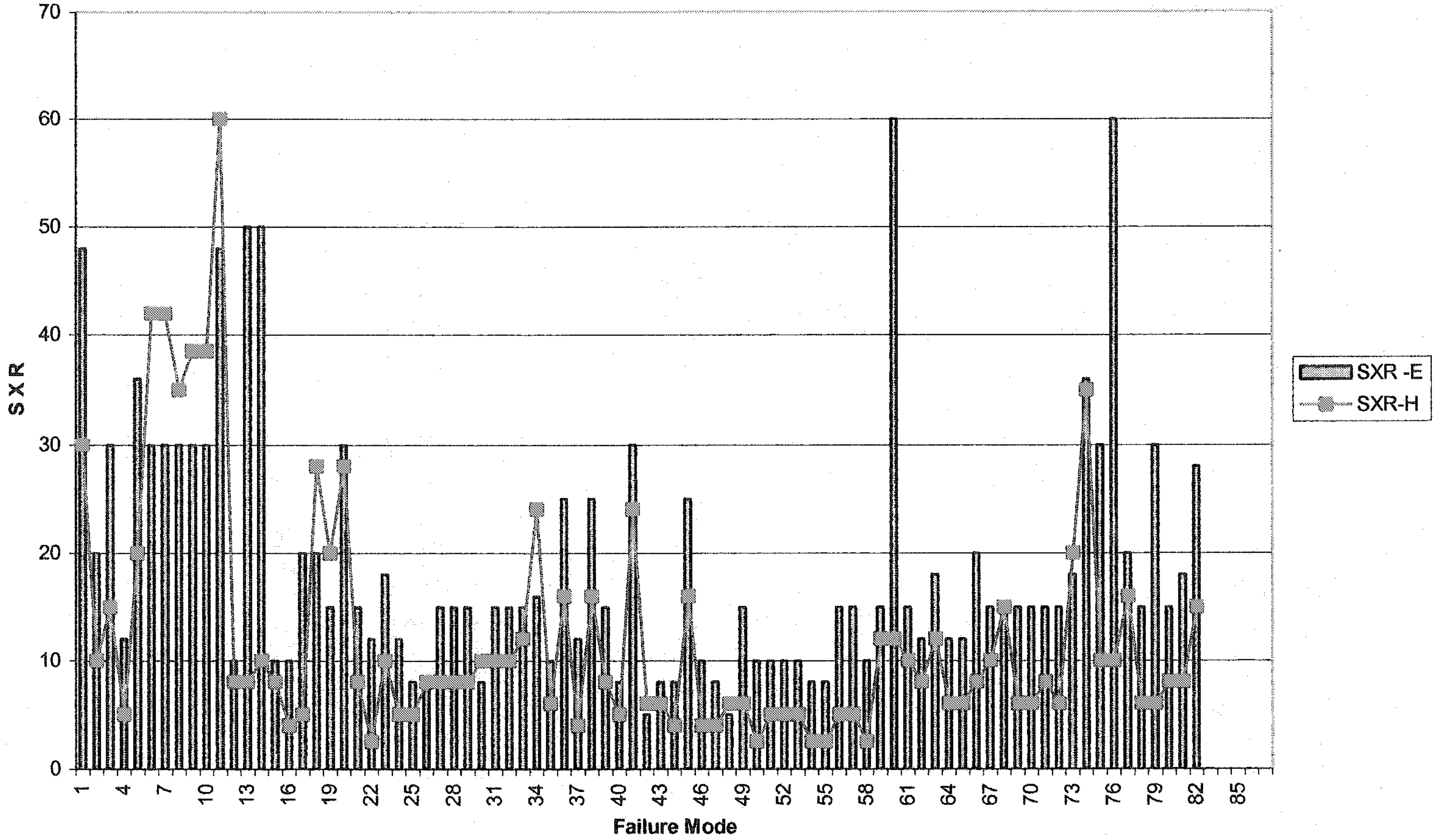


Figure 37, Severity x Repair – Platform C.

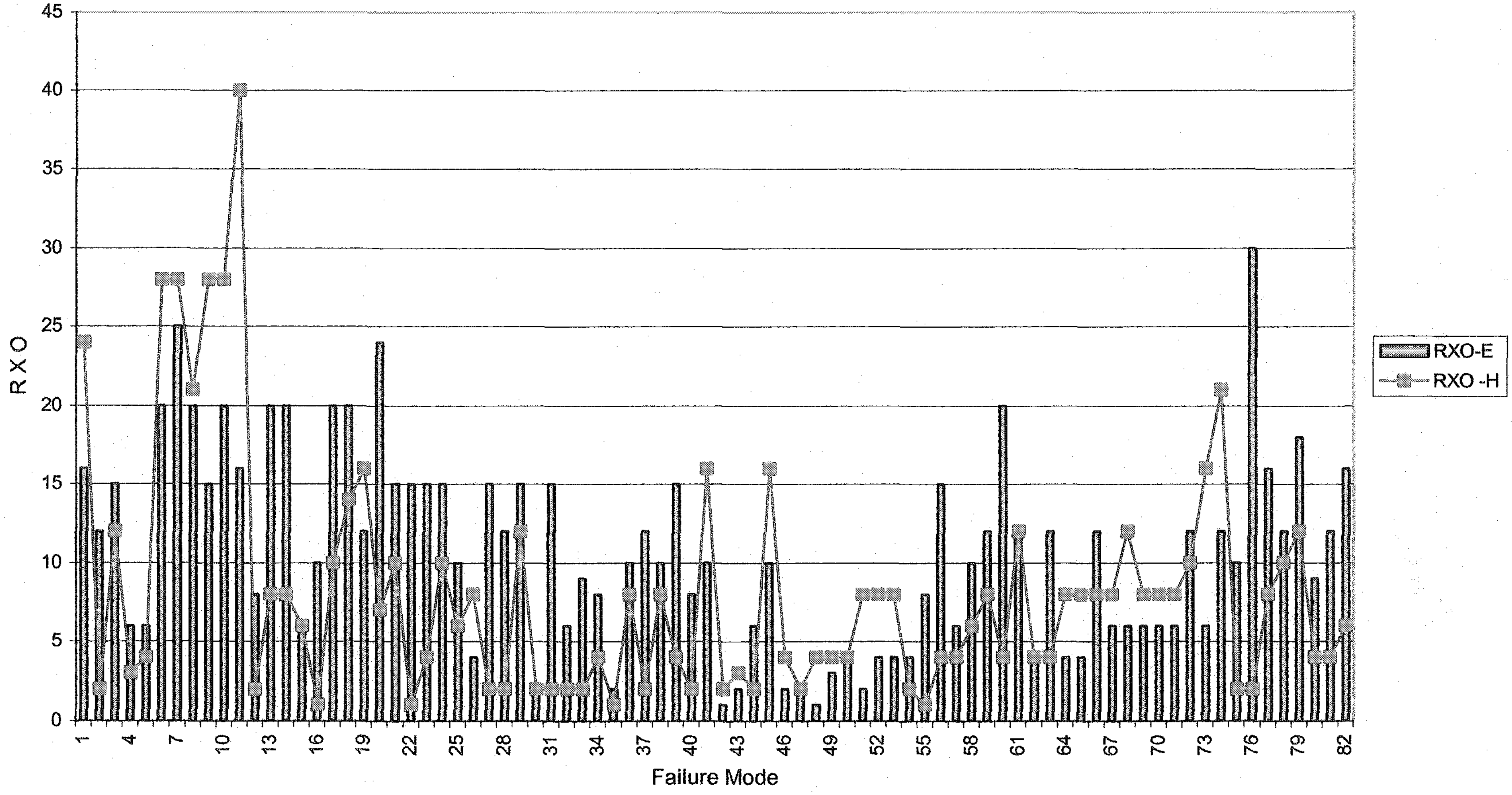


Figure 38, Repair x Occurrence – Platform C.

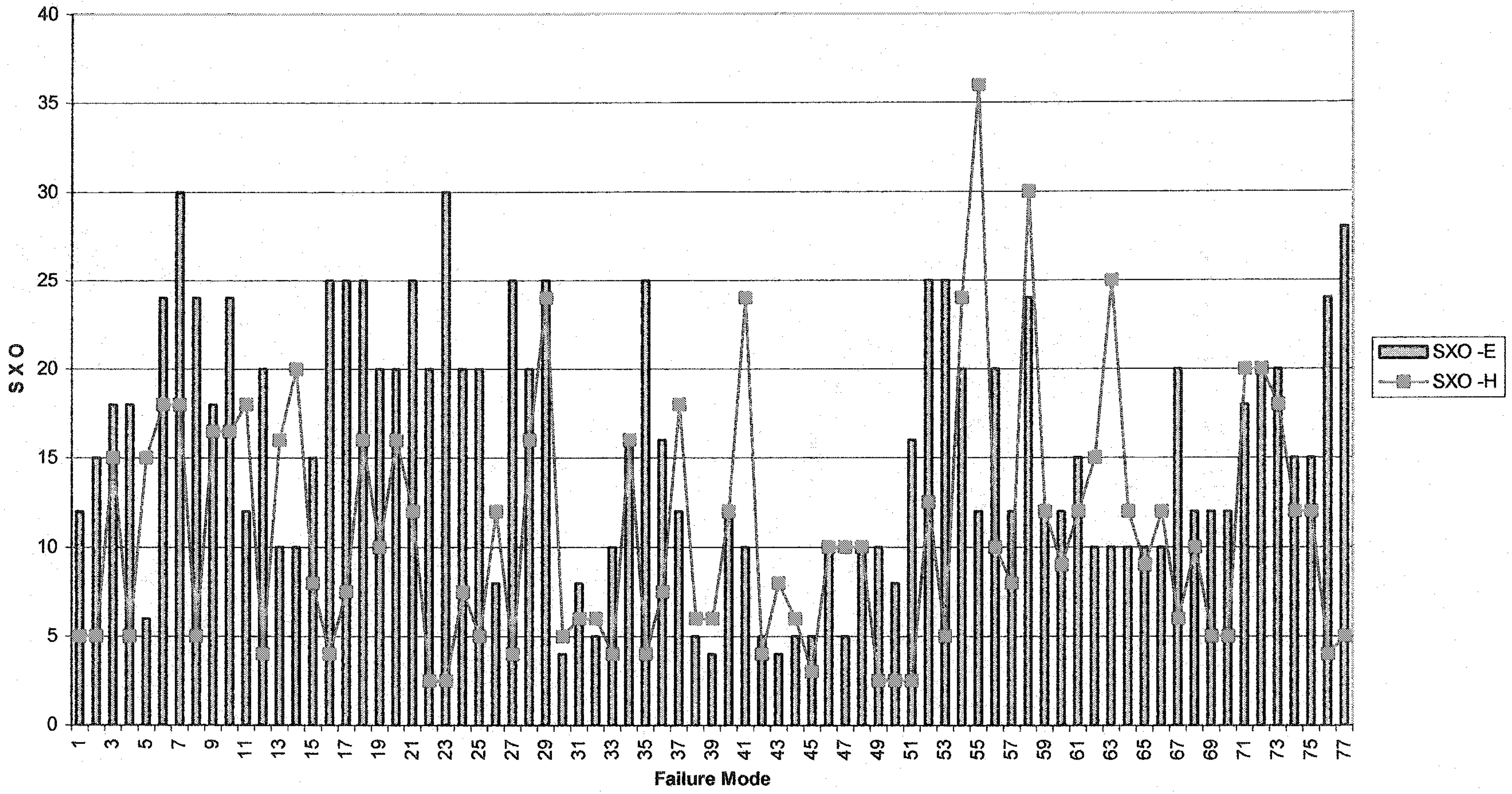


Figure 39, Severity x Occurrence – Platform D.

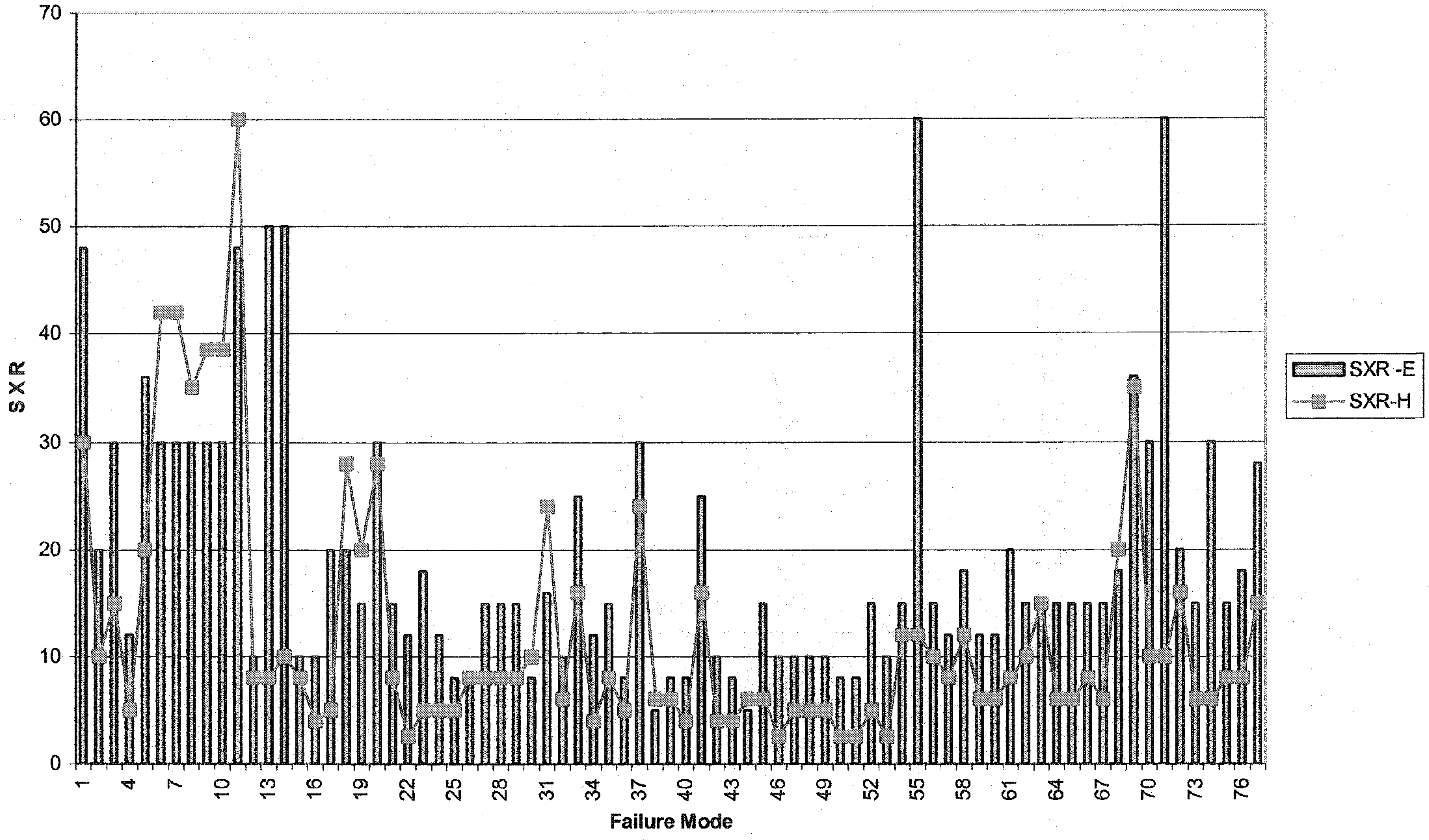


Figure 40, Severity x Repair – Platform D.

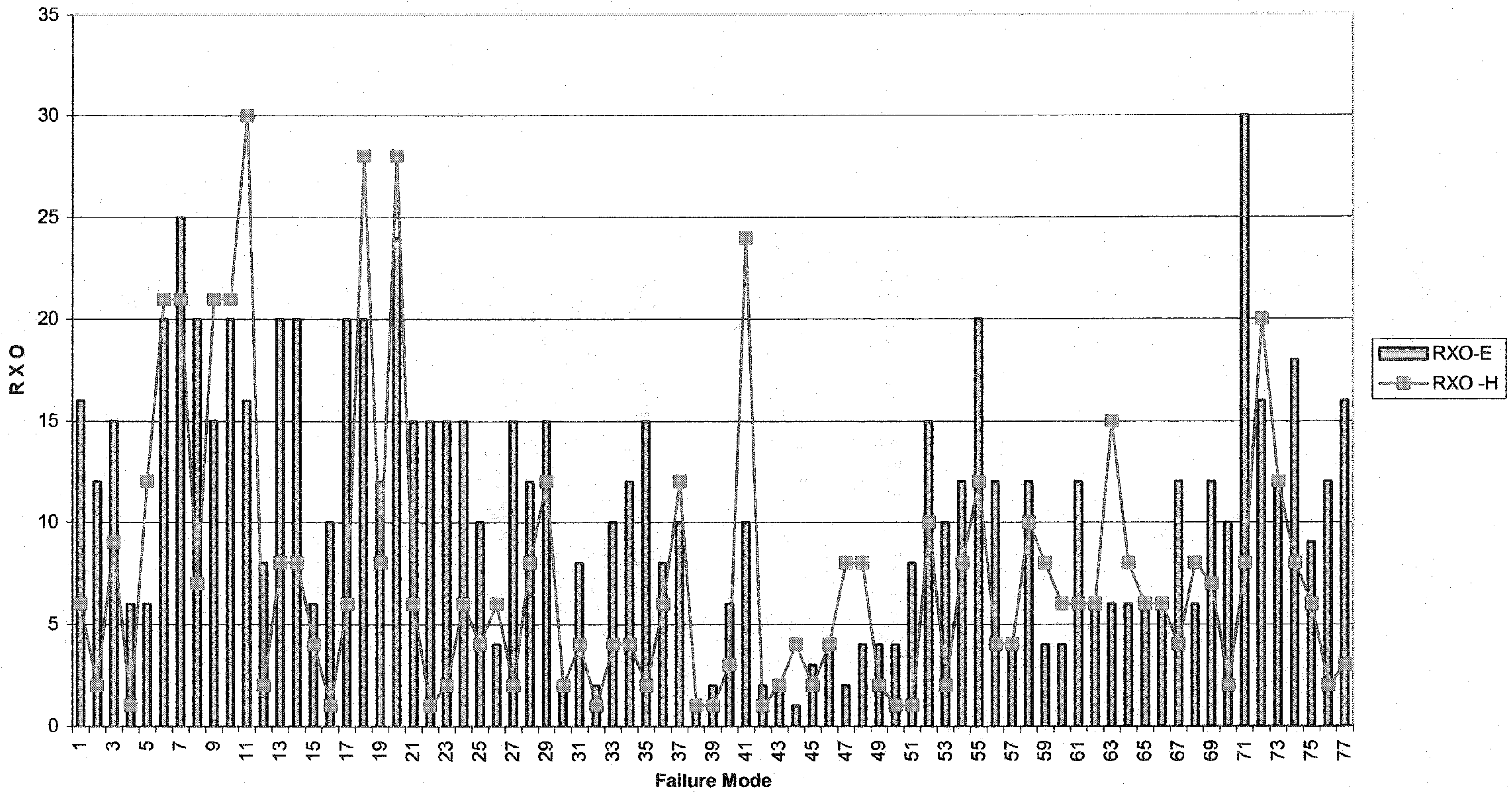


Figure 41, Repair x Occurrence – Platform D.

Two Factor Observations

It was observed that two of the three components in the model exerted greater influence over the resultant outcome of the model (occurrence and reparability). A Dot-Matrix plot of the two factors Figure 42 show how the data points for the combination of the two variables produces a more identifiable relationship to the resultant RPN in the historical model. While not as defined in the expert model it is still visibly apparent as figure 43 shows.

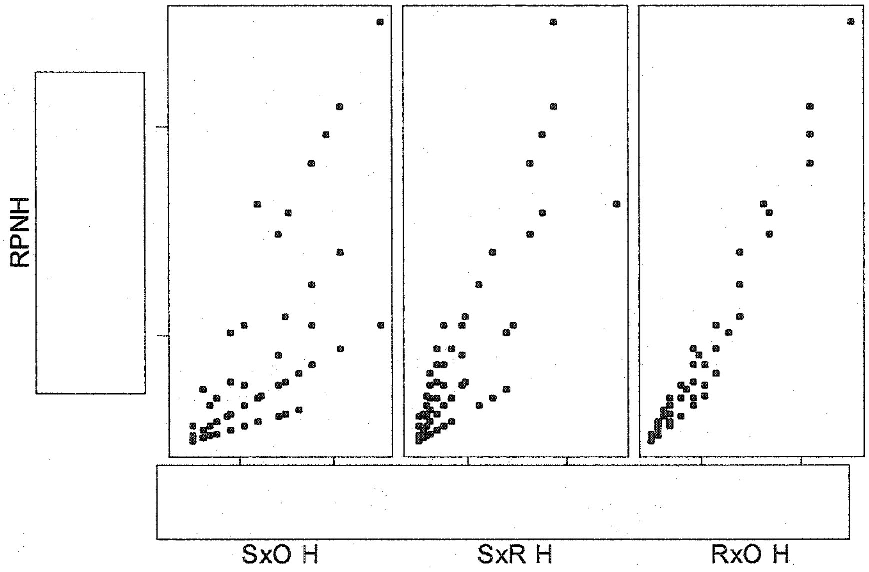


Figure 42, Dot matrix plot of two-factor product compared to three-factor RPN Model using Historical Data.

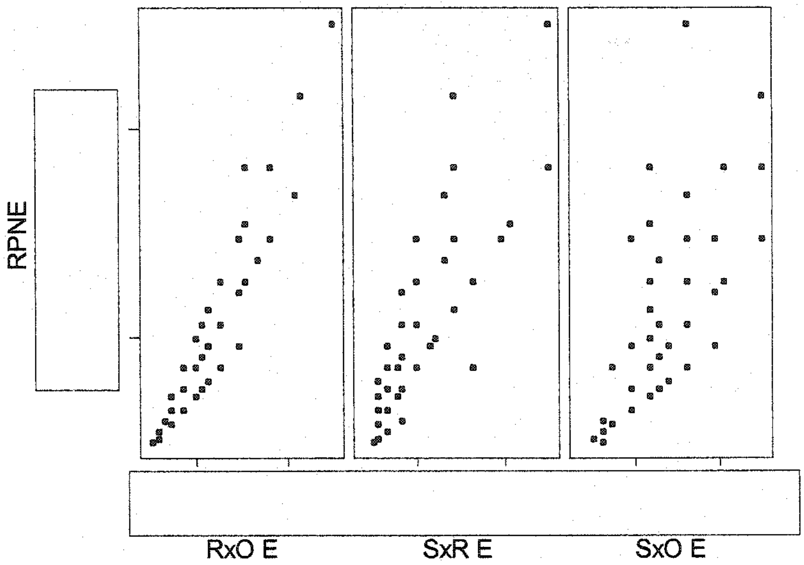


Figure 43, Dot matrix plot of two-factor product compared to three-factor RPN Model using Expert Data.

The overall system configuration supports this correlation as redundancy inherent in the system is used to minimize the severity of component failure impacting the ability of the system to support the mission of the metasystem.

By performing a best subsets regression of the factors yields the following concurrence to the graphical display of the dot-matrix plot of the data.

MINITAB OUTPUT FROM APPENDIX D

Best Subsets Regression: RPNH versus SevH, OccrH, RepH

```
Response is RPNH

                                                 O
                                               S c R
                                               e c e
                                               v r p
Vars   R-Sq   R-Sq(adj)      C-p          S    H H H

   1   64.2        63.8    117.9     14.054        X
   1   21.8        20.9    355.7     20.767    X
  *2   79.3        78.8     35.1     10.748      X X
   2   67.3        66.5    102.6     13.515    X   X
   3   85.2        84.7      4.0     9.1409    X X X
```

Best Subsets Regression: RPNE versus SevE, OccrE, RepE

```
Response is RPNE

                                                 O
                                               S c R
                                               e c e
                                               v r p
Vars   R-Sq   R-Sq(adj)      C-p          S    E E E

   1   54.5        53.9    282.7     16.349        X
   1   34.3        33.5    444.9     19.641    X
  *2   80.7        80.2     74.0     10.707      X X
   2   63.8        62.9    209.9     14.667    X   X
   3   89.7        89.3      4.0     7.8817    X X X
```

This was confirmed through a regression analysis and the resulting Pearson product moment coefficient of correlation (r) and the resulting coefficient of determination (r^2).

Regression Analysis: RPNH versus RxO H

```
The regression equation is
RPNH = - 5.03 + 3.33 RxO H

Predictor         Coef     SE Coef           T        P
Constant       -5.0337      0.9400       -5.35    0.000
RxO H          3.33065     0.09073       36.71    0.000

S = 5.722               R-Sq = 94.1%         R-Sq(adj) = 94.0%
PRESS = 3036.19         R-Sq(pred) = 93.53%

Analysis of Variance

Source             DF          SS          MS          F        P
Regression          1       44118       44118    1347.65    0.000
Residual Error     85        2783          33
  Lack of Fit      14        1607         115       6.93    0.000
  Pure Error       71        1176          17
Total              86       46901
```

Regression Analysis: RPNE versus RxO E

```
The regression equation is
RPNE = - 4.30 + 3.68 RxO E

Predictor         Coef     SE Coef           T        P
Constant        -4.295       1.673       -2.57    0.012
RxO E           3.6773      0.1372       26.79    0.000

S = 7.884               R-Sq = 89.4%         R-Sq(adj) = 89.3%
PRESS = 5596.52         R-Sq(pred) = 88.79%

Analysis of Variance

Source             DF          SS          MS          F        P
Regression          1       44620       44620     717.91    0.000
Residual Error     85        5283          62
  Lack of Fit      14        1352          97       1.74    0.066
  Pure Error       71        3931          55
Total              86       49902
```

Observations of Results

In comparing the two regression equations, it is noted that the slopes of the lines are different with the slope of the expert line being slightly steeper.

Chapter Summary

It is important to note that the expert RPN trended similarly to the historical RPN. This provides support for the acceptance of the expert's ability to forecast the systems behavior similarly to the use of the historical data. Comparison of the data graphically and through the use of both parametric and nonparametric statistical methods showed that the experts were similar in the trend of scoring the RPN variables with a tendency to score the severity and reparability variables higher than the variables equivalent developed from the historical data. This yielded higher RPNs. The experts were not as consistent with the occurrence factor in RPN model.

Through regression analysis and graphical comparison, it was also discovered that for the platforms understudy, occurrence and reparability were predominate factors in determining the RPN in the expert model, the historical comparative, and across all four platforms investigated.

CHAPTER VI

DISCUSSION OF RESULTS

Introduction

In the initial observation of the RPN components, it was also noted that there was little consistency or trend correlation to the occurrence factor between the experts and the historical data (Figure 44). This chapter will attempt to explain observed variations in the model and propose alternate theories for investigation.

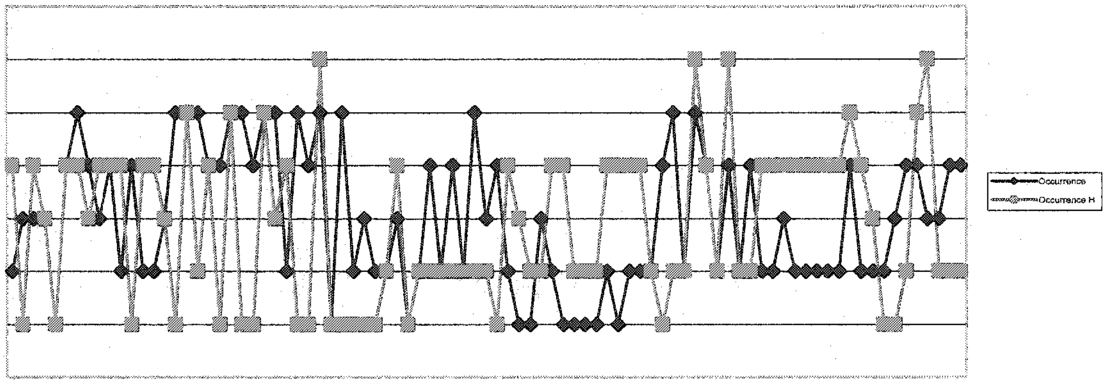


Figure 44, Comparison Occurrence E and Occurrence H – Platform A.

Development of RPN-Adjusted

In looking at the difference between the expert and historical, the concept of complementarity as it applies to complex systems seems to be in evidence. "Any two different perspectives (or models) about a system will reveal truths about that system that are neither entirely independent nor entirely compatible" (Clemson, 1984). A better explanation was

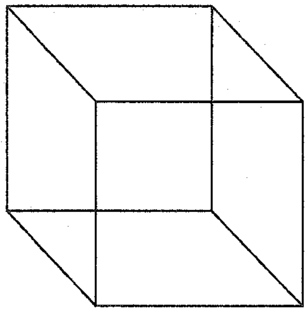


Figure 45, The Paradoxical Cube.

developed by Wolf (1989) in his attempt to describe the paradoxical cube:

> *At first you may see the upper most square in front, as if you were looking up at the cube. But if you take a second glance, you may find that you are suddenly looking down at the cube, and the bottom most square appears to pop out closest to you. As the observer, you have the choice of how you will observe the cube. It is your act of observation that resolves the paradox. In its abstract form, both the upper and lower squares of the illustration are, so to speak, in front at the same time or in the rear at the same time. But in viewing the illustration as a cube, you the observer create the experience of this tow dimensional form having rear and front faces. Your act of observing creates the picture in your mind that it is a cube. It is only a paradoxical cube when we, observers conditioned to think that everything we see must be solid, insist that "it" is a solid cube. Then the cube appears to jump from one perspective to another, seemingly playing tricks on us.*

The experts are preconditioned due to recent experiences with the systems under study that their perspective is shifted to the more recent occurrences. Checkland (1999) refers to this phenomenon as the viewpoint of the observer. The experts due to their proximity to the system are unable to look past the recent time frame to yield an accurate opinion of the 5-year period of actual occurrence.

As occurrence is a predominate factor in computing the RPN, as previously shown, an adjusted RPN (RPNadj) was developed using the historical occurrence data, and the expert severity and reparability data and then compared to the RPNH. This was necessitated to compensate for the narrow view of the experts on the occurrence component of the model. The resultant graphs are shown as figures 46-49.

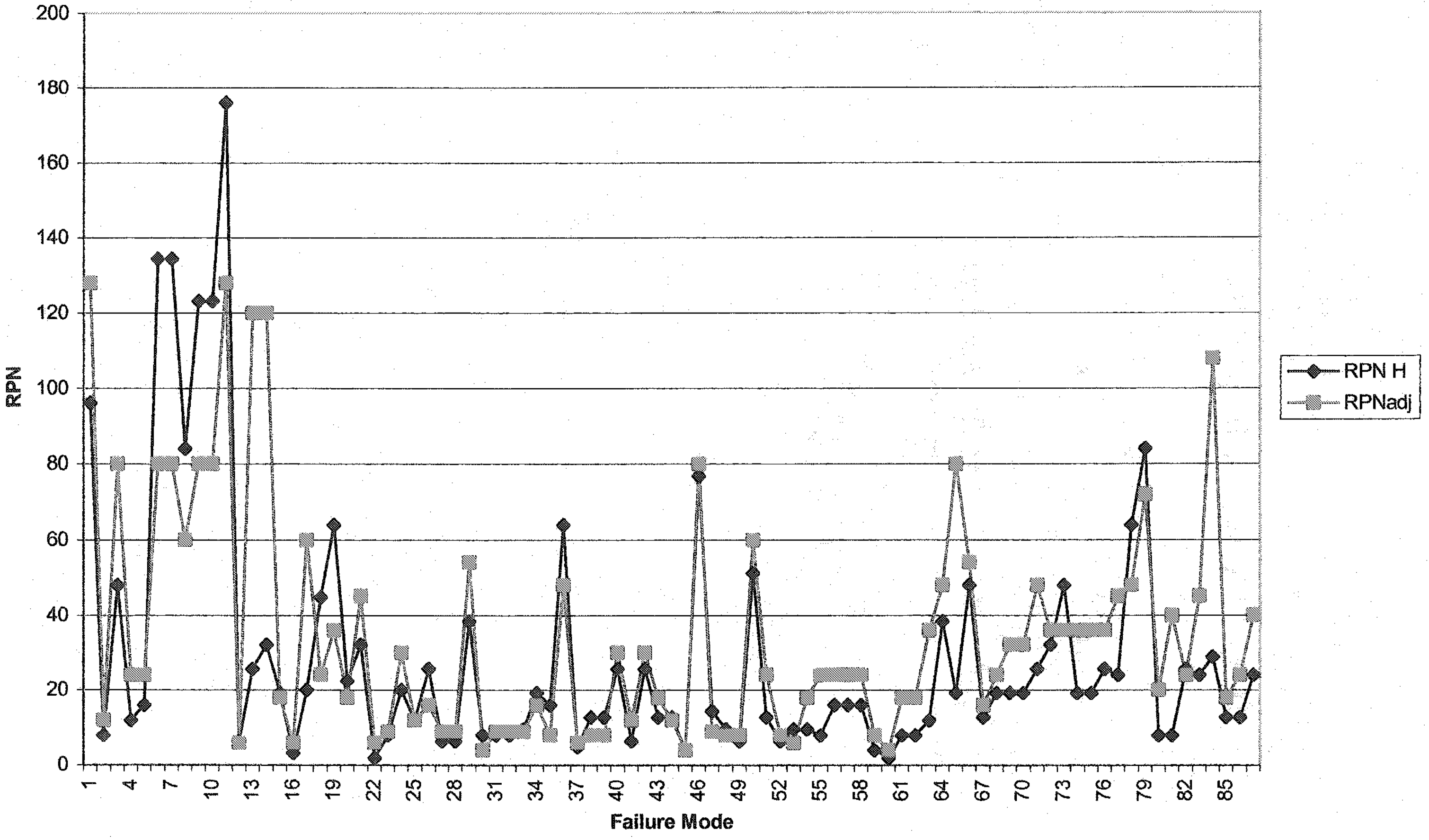


Figure 46, Comparison of RPN-Adj to RPN H – Platform A.

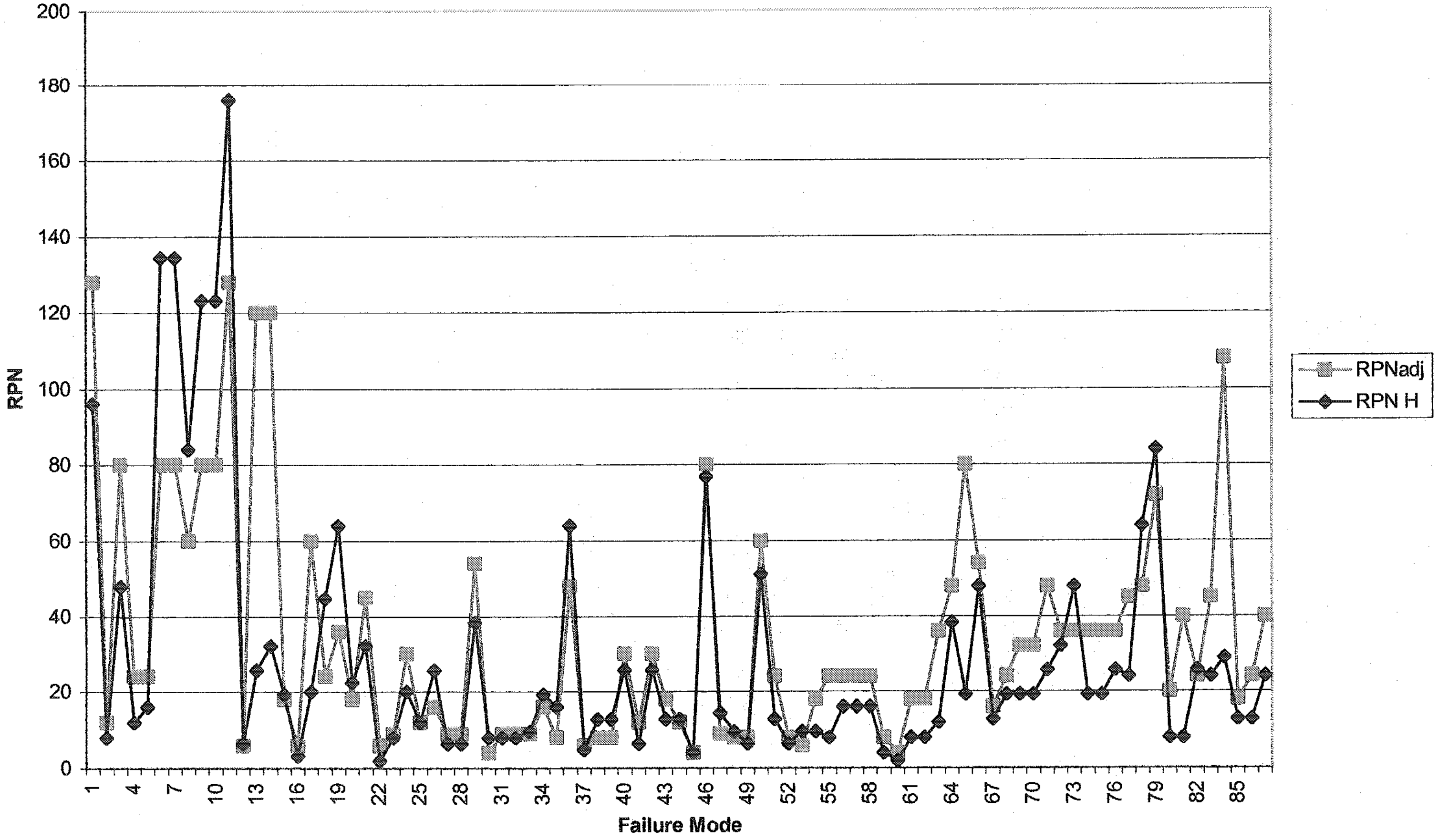


Figure 47, Comparison of RPN-Adj to RPN H – Platform B.

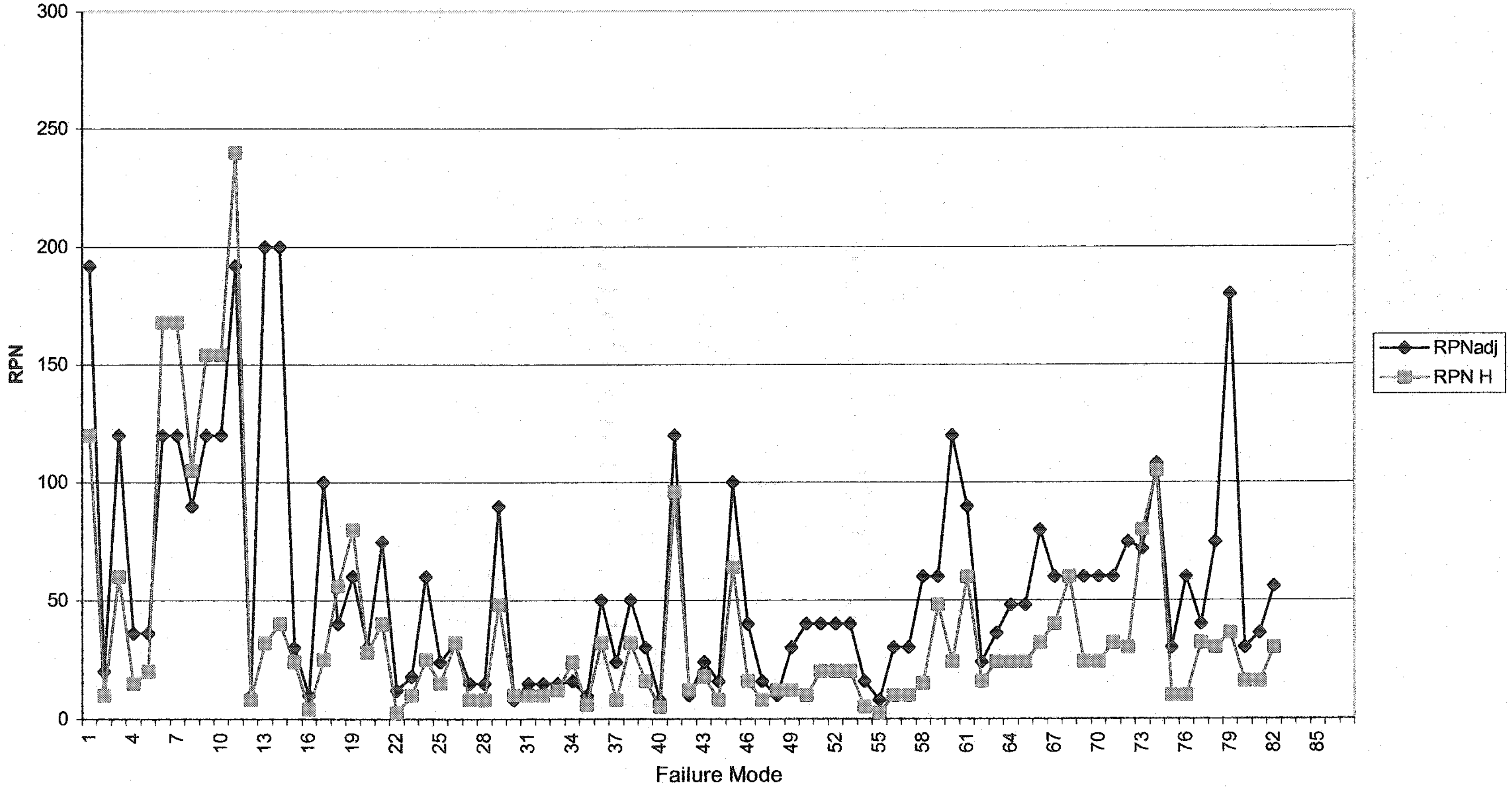


Figure 48, Comparison of RPN-Adj to RPN H – Platform C.

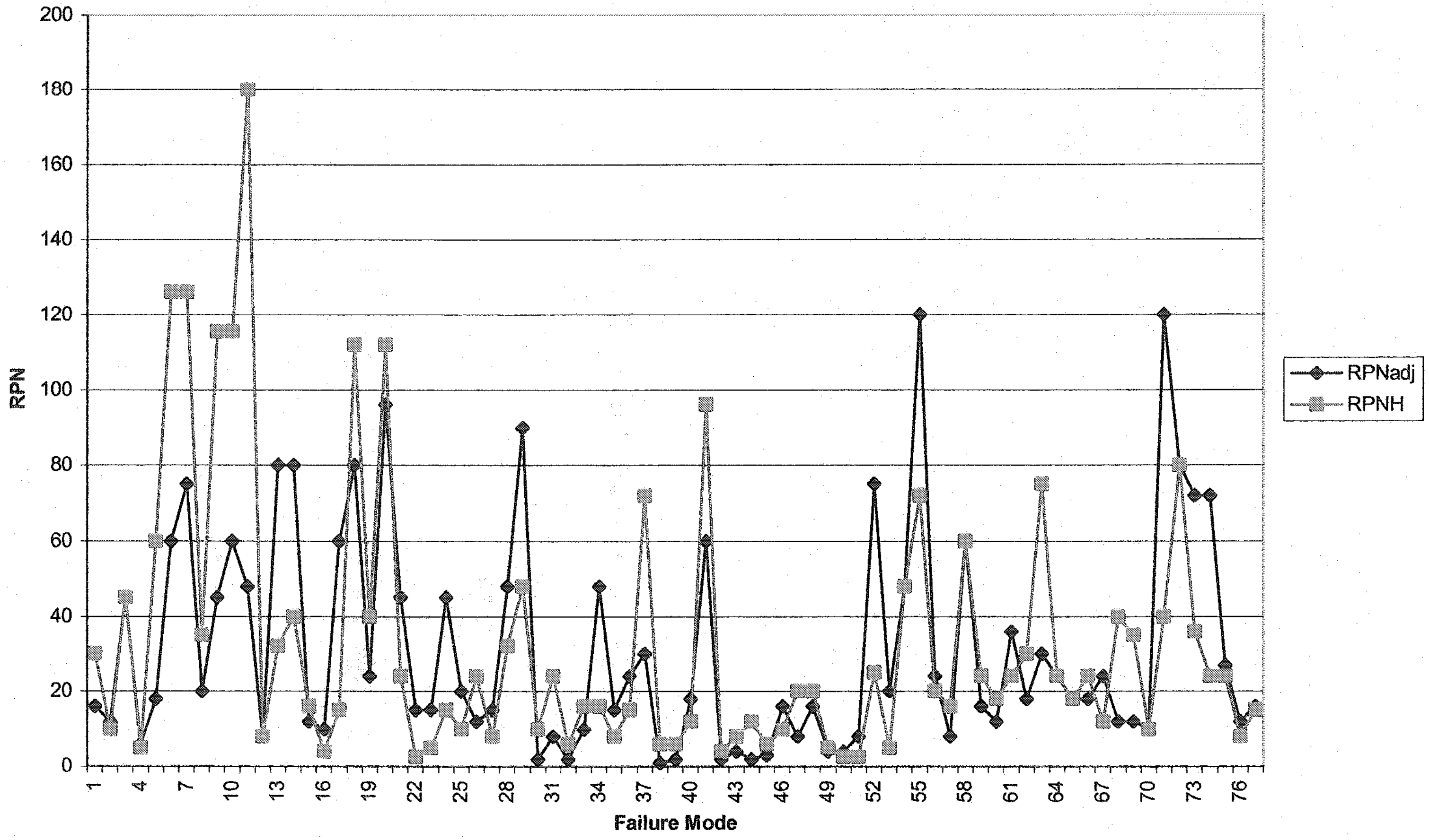


Figure 49, Comparison of RPN-Adj to RPN H – Platform D.

Best Subsets Regression: RPNadj versus SevE, RepE, OccrH

```
Response is RPNadj

                                                      O
                                                  S R c
                                                  e e c
                                                  v p r
Vars  R-Sq  R-Sq(adj)       C-p          S        E E H

   1  52.2       51.7     278.3     19.011          X
   1  36.1       35.3     400.6     21.994            X
  *2  87.5       87.2      13.5     9.7799          X X
   2  55.6       54.6     254.8     18.437        X X
   3  89.0       88.6       4.0     9.2208        X X X
```

Regression Analysis: RPNadj versus RXO-A

```
The regression equation is
RPNadj = - 0.750 + 3.36 RXO-A

Predictor        Coef     SE Coef         T        P
Constant      -0.7505      0.6143     -1.22    0.223
RXO-A         3.36161     0.04775     70.40    0.000

S = 7.016               R-Sq = 93.4%         R-Sq(adj) = 93.4%
PRESS = 17676.9         R-Sq(pred) = 93.23%

Analysis of Variance

Source            DF        SS        MS        F        P
Regression         1    243947    243947  4956.33    0.000
Residual Error   352     17325        49
  Lack of Fit     13      6063       466    14.04    0.000
  Pure Error     339     11262        33
Total            353    261272
```

Summary

Comparison of the RPNH to the RPNadj yielded an improved test of the initial hypothesis where in that the adjusted RPN scores were equal to or exceeded the historical RPN 68% of the time in Platform A, 85% of the time in Platform B, 76% of the time in Platform C, and 83% of the time in Platform D. in 82% of the cases modeled. SPSS outputs for testing RPNadj and RPNH are located in Appendix C and are summarized here in Table 9.

Summary Table Nonparametric Statistical Test			
RPNHIST - RPNadj		***RPNHIST < RPNadj***	**57**
Platform A		***RPNHIST > RPNadj***	**28**
(60%)	**68%**	***RPNHIST = RPNadj***	**2**
8% increase		***TOTAL***	**87**
RPNHIST - RPNadj		***RPNHIST < RPNadj***	**62**
Platform B		***RPNHIST > RPNadj***	**13**
(71%)	**85%**	***RPNHIST = RPNadj***	**12**
14% increase		***TOTAL***	**87**
RPNHIST - RPNadj		***RPNHIST < RPNadj***	**57**
Platform C		***RPNHIST > RPNadj***	**20**
(74%)	**76%**	***RPNHIST = RPNadj***	**5**
2% increase		***TOTAL***	**82**
RPNHIST - RPNadj		***RPNHIST < RPNadj***	**62**
Platform D		***RPNHIST > RPNadj***	**13**
(82%)	**83%**	***RPNHIST = RPNadj***	**2**
1% increase		***TOTAL***	**77**

Table 9, Summary of Nonparametric Statistical Test, RPNadj Platforms A-D.

For consistency, a best subset regression was preformed on the adjusted model showed the relationship of reparability and occurrence held as the dominating factors in the three-factor RPN model and is included in Appendix D.

The use of the adjusted RPN showed a marked similarity in shape to that of the historical RPN over that of the original expert RPN. While the increases in the nonparametric statistical test were minimal for Platforms C and D, visual comparison of the graphs show greater trend similarity with the historical RPN and the adjusted RPN than with the expert RPN.

CHAPTER VII

RESEARCH CONCLUSIONS

Introduction

This chapter discusses the conclusions drawn from the research. Recommendations for further research on complex systems using high-level FMEA, as a basis for development of a holistic perspective on the behavior, are also discussed.

Conclusions

This research tested hypotheses focusing on the ability of experts to develop risk priority numbers consistent with the historical data on a legacy system. The results of the research extend the scholarly literature by developing a new use for FMEA, commonly used in research and design, and expanding it as a tool that allows for a targeted assessment of system components when compared to historical failure and repair data. Use of the expert provides for a more holistic approach to modeling of the system under study than that of historical data, as the experts may have greater insight into the ability of the current personnel to repair and maintain the equipment.

The initial research question posed in the dissertation was, "can a methodology that uses the expert knowledge, elicited from system experts through a high level FMEA, be used to create a knowledge based decision support system to aid in the assessment of legacy systems?"

Consistent trending of the expert RPN and the proposed adjusted RPN indicate that the expert behavioral model is consistent with the historical behavior of the systems under study.

It can also be noted that the expert tended to evaluate the factors of repair and severity at higher levels than the historical data indicated. This could indicate that the expert has a more holistic view of the system as it relates to the much larger system and group of systems that comprise the ship thus more accurately reflecting the effects of the system under study on the ships mission availability.

Conversely, the experts due to their proximity to the system are unable to look past the recent time frame to yield an accurate opinion of the 5-year period of actual occurrence. As discussed in the previous chapter, it became apparent to the researcher that the experts lacked the capacity to recall the failures occurring over a 5-year period. With the concept of complementary, it became insightful that the perspective of the expert was clouded by recent events that could be easily recalled. As the historical data used to provide the actual failures for the past five years was readily available, the RPN adjusted was developed and presented as a means to overcome this obstacle in future research.

As expected the experts resultant RPN, and the RPN adjusted, was greater than or equal to the RPN developed from historical data relating to the actual system behavior in the majority of the failures investigated. This indicates a propensity, as stated in the first hypothesis, that the experts will be more holistic in their assignment of the variables. Other conclusions from analysis of the data are as follows:

1. System design has influence over the outcome of the RPN.

   In the system studied for this research, initial design of the system provided redundant components that mitigated the severity of the component failure in regards to system behavior and response to component failure. As a result of this design, severity of component failure exerted less influence than the other variables in the model. Design for ease of repair and robust system designs would intuitively yield reductions in the resultant RPN as well.

2. Reparability of the system is a function of the complex interaction of the personnel with the system and has a tendency to exert influence over the outcome of the RPN model.

   Analysis of the historical data regarding repair and the expert's opinion were, while similar, often differing. The experts tended to score reparability of the system at higher levels due to their belief that the personnel lacked the necessary skills required in the performance of the tasks necessary to repair the system. It is the expert's evaluation of the personnel ability that gives depth and perspective (a more holistic view) to the model that cannot be captured from the historical data

3. The characteristics of complex systems, i.e. complementarity, self-organization and system darkness, have a profound effect on the ability to model system behavior.

   The experts are human beings that have had a great deal of interaction with the system; as such, it is their experience with the system under study that a holistic perspective is trying to incorporate. The complex system and any representation of the complex system can only be described by what is known, observed or suspected. Unknown, unobserved, unrepresentative, and emergent characteristics will be present. System behavior and informal structure emerge only through system operation, regardless of the detailed design efforts conducted prior to system deployment. In the legacy system it is even more apparent because the system has been deployed for a great length of time. In order to capture these aspects and quantify them for use in development of management decisions, it is paramount to cast a wide net through the use of experts on the system to garner the vantage point or frame of reference when viewing the system that reveals the most knowledge about the system in it current operational state.

Recommendations

Maintenance productivity is a critical element of Engineering Management and Systems Engineering. A significant issue in developing and implementing productive maintenance systems involves development and analysis of data that can direct changes and identify high priority areas. This research supports a systemic approach to predictive maintenance programs. This approach employs a modified form of Failure Mode Effects Analysis with a Risk Priority System ranking system that employs expert judgment. While this fills a critical gap in the literature, it leads to the following recommendations for future research in this area:

1. Similar research should be done on a variety of systems to map the resulting Expert RPN against the Historical data. While the research looked at single system on multiple platforms, it is believed that based on initial system design, variables in the RPN model may have changing predominance in the outcome of the resultant RPN.

2. While current FMEA looks at three factors in development of the RPN, it is suggested that this or a similar study look at the addition of a fourth variable – cost. While it may be construed as a factor looked upon in modeling severity and reparability, using cost

as an additional factor may have benefit in looking at the system model in a more holistic manner.

3. Use of different means to elicit the expert opinion (other than the Delphi method used in this research) might result in differing results to the expert model. Testing the elicitation techniques against each other may provide greater insight into the best way to extract the knowledge held by the experts in this field.

4. Using the historical model as a test basis, disparity in the two models may be used to target resources for improvement in the system. This would allow for the targeted deployment of resources and time when dealing with a legacy system that is costly to assess.

Failure Mode Effects Analysis is a useful tool in research and design, by adapting the model slightly it appears to be even more useful in evaluation of legacy systems. Prediction of problems before they occur can minimize system downtime and lead to targeted proactive maintenance planning. The methodology offered in the research provides a framework for the use of experts to provide engineering managers a more holistic perspective of a legacy system when making maintenance assessments.

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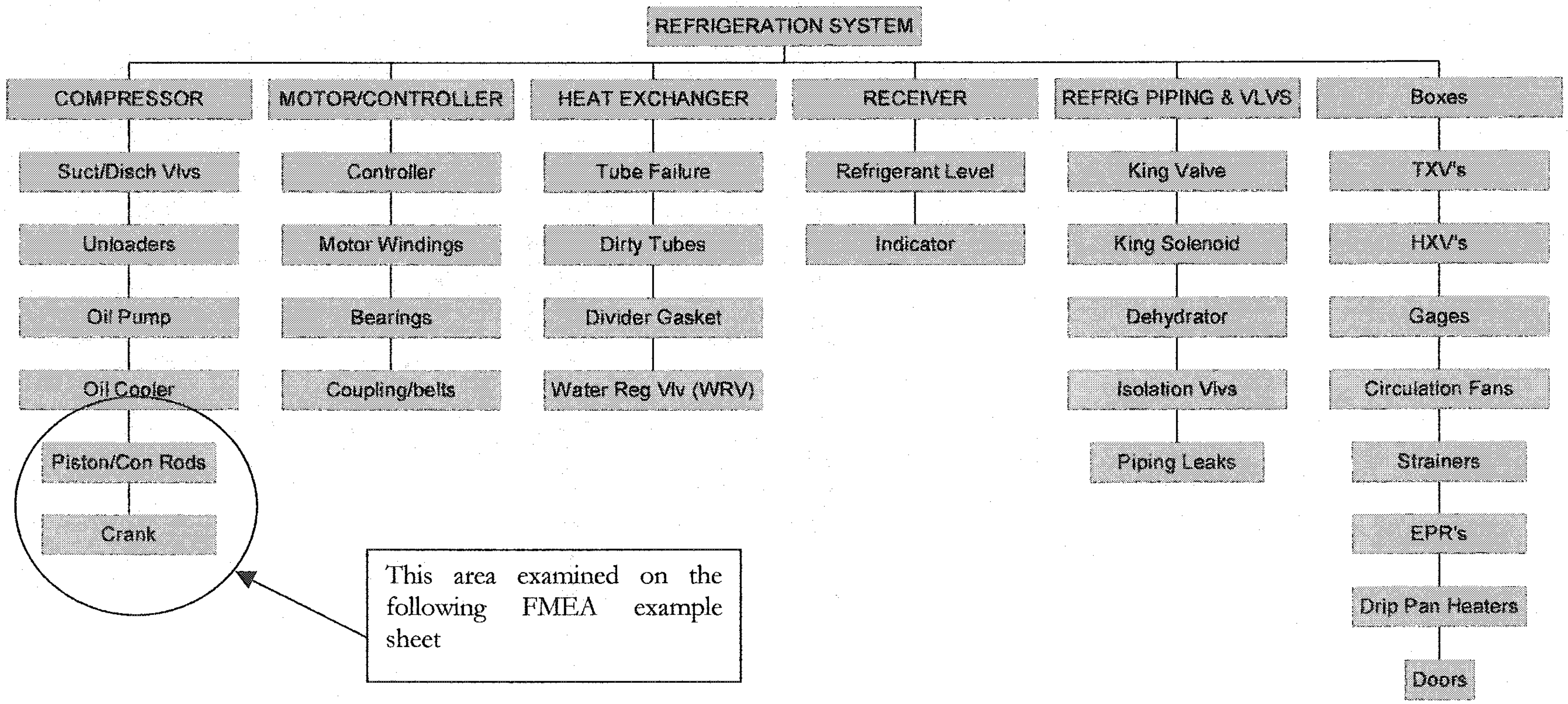
Appendix A

Figure A-1: Example of Fault Tree System Diagram

Note: Fault tree may begin with components as shown here and may evolve to functional breakdown. For example, the compressor in the left column may contain "oil system" and include the pump and cooler.



This area examined on the following FMEA example sheet

Table A-1: FMEA Worksheet Example

Top level: Refrigeration system   Equipment Description: Compressor   Sub component: Piston and connecting rod

Ship: ____________________   SEMAT II date: ____________________   Prepared by: ____________________

FMEA Number: ____________ Date: ________ Revision: ____________ Page ______ of ________

											SEMAT II Results				
Function	**Failure Mode**	**Potential cause of failure**	**Severity**	**Impact of Failure**	**Occurrence**	**Probability of Occurrence**	**Repair**	**Probability of Repair**	**RPN**	**Recommended SEMAT II action**	**SEMAT II action taken**	**Severity**	**Occurrence**	**Detection**	**Reduced RPN**
Piston connecting rod System failure	Cracked rod or arm	Metal failure	6	System down overhaul needed	1	Extremely infrequent- no indication of problems in 3-M or ICAS for this compressor	8	Cannot be repaired by ship's crew , significant part issues.	48	ICAS and 3-M do not indicate problems. Level 1 recommended		6	1	8	48
		Oil pump failure	6	System down overhaul needed	5	Pump and switch must both be bad for failure.	8	Oil pressure switch shuts down compressor – occasional failure	240	Level 2- Test pump and replace pressure switch	Level 2 for system	6	3	8	144
		Clogged oil filter.	6		5	Flow switch must fail to damage compressor	8		240	Level 2 – replace all sensors		6	3	8	144
	Ring failure	Oil pump failure													

Interpretation: Based on FMEA, summary recommendation may be for Level 2 maintenance since no indicators show that extensive Level 3 maintenance is justified.

TABLE A-2 SEVERITY RATING FOR FMEA

Consider these criteria when selecting the failure severity impact rating

Effect	Rank	System Description	Mission Impact	CASREP potential
No effect	1	Required for overall integrity of other than essential or backup system.	No effect to personnel, ship, or mission	None
Very slight	2	Required for overall integrity of other than essential or backup system.	Very slight effect to personnel, ship, or mission	Minimal possibility of C-2.
Slight	3	Required for efficient performance of ship's mission, or Important safety or damage control item, or Required for overall integrity of equipment or systems that are not essential, but are required as backups in case of primary system failure.	Slight effect to personnel, ship, or mission	Possible C-2 (25% or less)
Minor	4	Required for efficient performance of ship's mission, or Important safety or damage control item, or Required for overall integrity of equipment or systems that are not essential, but are required as backups in case of primary system failure.	Minor effect to personnel, ship, or mission	Normally C-2 in at least 50% of cases
Moderate	5	Required for efficient performance of ship's mission, or Important safety or damage control item, or Required for overall integrity of equipment or systems that are not essential, but are required as backups in case of primary system failure.	Moderate effect to personnel, ship, or mission,	Usually C-2 in at least 75% of cases, chance of C-3 CASREP is 10% or less
Significant	6	Required to sustain performance of ship's mission, orExtremely important safety or damage control item, orRequired to maintain overall integrity of ship or a system essential to ship's mission.	Significant effect to personnel, ship, or mission,	Possible C-3 in at least 25% of cases
Major	7	Required to sustain performance of ship's mission, or Extremely important safety or damage control item, or Required to maintain overall integrity of ship or a system essential to ship's mission,.	Major effect to personnel, ship, or mission	Likely C-3 (over 50% of cases), C-4 is possible (less than 10% of cases)
Serious	8	Required to sustain performance of ship's mission, or Extremely important safety or damage control item, or Required to maintain overall integrity of ship or a system essential to ship's mission.	Serious effect to personnel, ship, or mission,	Definite C-3. C-4 possible in 50% or less of cases
Extreme (with warning)	9	Required for performance of ship's mission, or Critical safety or damage control issue.	Extreme effect to personnel, ship, or mission.	Normally C-4 (over 50% of cases)
Hazardous (without warning)	10	Required for performance of ship's mission, or Critical safety or damage control issue.	Hazardous effect to personnel, ship, or mission.	Normally C-4 (over 50% of cases)

Table A-3 FMEA Occurrence Guidelines

Rate the probability of failure occurrence over the next 12 months of operation considering the current state of the system including ICAS monitoring and 3M data.

Occurrence	*Rank*	Estimated MTTF (hours)	Probability of failure in 8,500 hours (12 months)	Detection / Sensor Criteria	Typical Occurrence Description
Almost never	1	MTTF > 100,000	P (failure) ~ 1%	Current controls / detectors, or maintenance information / procedures almost always detect the failure. Reliable detection controls are known and used in similar processes. Audible alarm cannot be ignored. ICAS monitors and alarms this failure so it does not occur.	Failure is extremely unlikely, history shows no reason for failure prediction.
Remote	2	MTTF~ 100,000	P (failure) ~ 5%	Very high likelihood current controls, detectors and / or maintenance procedures will detect the failure.	Failures very rare.
Very slight	3	MTTF~ 75,000	P (failure) ~ 10%,	High likelihood current controls, detectors and / or maintenance procedures will detect the failure.	Failures occur infrequently.
Slight	4	MTTF ~ 40,000	P (failure) ~ 25%,	Moderately high likelihood current controls, detectors and / or maintenance procedures will detect the failure.	Failures occur occasionally.
Low	5	MTTF ~ 25,000	P (failure) ~ 40%,	Medium likelihood current controls, detectors and / or maintenance procedures will detect the failure.	Failures occur with moderate frequency
Medium	6	MTTF ~ 10,000	P (failure) ~ 60%,	Low likelihood current controls, detectors and / or maintenance procedures will detect the failure.	Failures occur with regularity
Moderately High	7	MTTF ~ 5,000	P (failure) ~ 75%,	Slight likelihood current controls, detectors and / or maintenance procedures will detect the failure.	System fails often.
High	8	MTTF ~ 3,000	P(failure) ~ 90%,	Very slight likelihood current controls, detectors and / or maintenance procedures will detect the failure.	Failures will occur in the large majority of cases
Very High	9	MTTF ~ 2,000	P(failure) ~ 95%,	Remote likelihood current controls, detectors and / or maintenance procedures will detect the failure.	Very high failure rate.
Almost Certain	10	MTTF ~ 1,000	P(failure) ~ 99%,	No known controls, detection or maintenance procedure available to detect failure	Failure almost certain.

Resolution: If actual numerical value falls between two values – always select the higher value. If the team has a disagreement in the ranking, use the following approach:

- If adjacent categories, average the difference. For example, one member says 5 and one member says 6, the ranking would be 5.5. If the disagreement is more than one category, consensus must be reached – even with one holdout. This indicates a serious difference in severity. Do not use average or majority. Team may not agree 100% but able to "live with it." Everyone must have ownership

Table A-4 FMEA Remediation Guidelines

Rate the probability of remediating the failure based on whether it can be detected, mitigated, and / or prevented by maintenance actions, controls, inspections, or maintenance information (ICASE). Low - ranked failure modes are not productive areas for SEMAT II activity.

Detection	Rank	**Probability of Detection**	**Repair context**	**Parts availability**	**Deployment Repair Summary**
Almost certain	1	P (remediation) > 99%	Easily repairable by ship's force 99% or more	Parts readily available without delays 99% or more	Failure easily repaired in all cases
Very High	2	P (remediation) ~ 95%	Repairable by ship's force in at least 95% of cases	Parts readily available, delays seldom occur very infrequently	Failure easily repaired in essentially all cases
High	3	P (remediation) ~ 90%	Normally repairable by ship's force in at least 90% of cases	Parts normally available, delays seldom occur	Failure easily repaired in many cases
Moderately High	4	P (remediation) ~ 75%	Often repairable by ship's force in at least 75% of cases.	Parts normally available with minor delays	Failure usually repaired without problems in most cases
Medium	5	P (remediation) ~ 60%	Usually repairable by ship's force (in about 60% of cases) and 10% require FTA support	Parts usually available	Failure usually repaired but problems do occur in some cases.
Low	6	P (remediation) ~ 40%	Occasionally repairable by ship's force (in 10% of cases) and at least 25% requiring FTA.	Parts occasionally available	Failure often repaired but significant logistics effort required in many cases
Slight	7	P (remediation) ~ 25%	Seldom repaired by ship's force (less than a 5%) and often requiring FTA in 50% or more cases,	Parts seldom available and may require long lead time	Failure is repairable but requires major logistics effort in most cases
Very slight	8	P (remediation) ~ 10%	Unlikely repair by ships forces, usually FTA to accomplish repairs in at least 75% of cases	Parts require long lead time	Failure is usually repairable but with significant logistics support problems.
Remote	9	P (remediation) ~ 5%	Not repairable by ships forces, always requires FTA to accomplish repairs	Parts not available and long lead required	Failure is not repairable without major logistic effort in essentially all cases
Almost Impossible	10	P (remediation) < 1%	Not repairable by ships forces, always requires FTA to accomplish repairs	Parts not available and long lead required	Failure is not repairable without major logistic effort in essentially all cases

Resolution: If actual numerical value falls between two values – always select the higher value. If the team has a disagreement in the ranking, use the following approach: If adjacent categories, average the difference. For example, one member says 5 and one member says 6, the ranking would be 5.5. If the disagreement is more than one category, consensus must be reached – even with one holdout. This indicates a serious difference in severity. Do not use average or majority. Team may not agree 100% but able to "live with it." Everyone must have ownership.

Appendix B

LP AIR SYSTEM EXPERT QUALIFYING QUESTIONAIRE

Name:____

Date:____________________

Education:
High School Graduate ___

Undergraduate: ___ Degree: ______________________ Date of Degree: _______

Graduate Degree(s): ______________________________

____

Other Training:

____

____

____

____

____

____

____

____

____

____

Current Employer: ____

Employer Address: ____

Position: ____

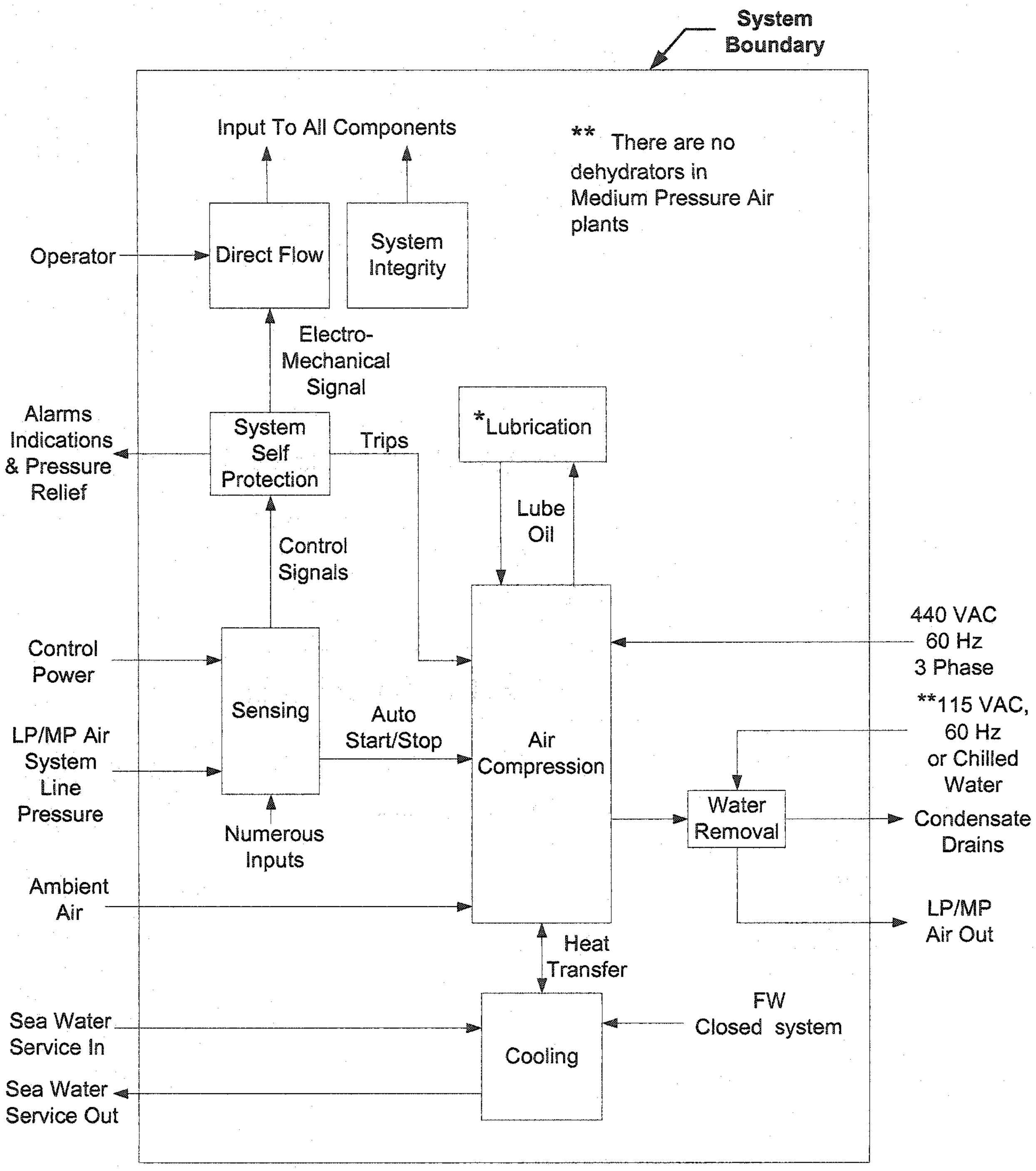
Contact Information:

Work Phone: _______________
Email: ____________________

General Information Packet

LP AIR SYSTEM

For general purposes, it will be assumed that LP Air system is comprised as indicated with a rotary helical screw type compressor.


System Boundary
Input To All Components
** There are no dehydrators in Medium Pressure Air plants
Operator
Direct Flow
System Integrity
Electro-Mechanical Signal
Alarms Indications & Pressure Relief
System Self Protection
Trips
*Lubrication
Lube Oil
Control Signals
Control Power
Sensing
Auto Start/Stop
Air Compression
440 VAC 60 Hz 3 Phase
**115 VAC, 60 Hz or Chilled Water
LP/MP Air System Line Pressure
Numerous Inputs
Water Removal
Condensate Drains
Ambient Air
LP/MP Air Out
Heat Transfer
FW Closed system
Sea Water Service In
Cooling
Sea Water Service Out

Cooling

1. Oil Pump
2. Oil Sump
3. Fresh water (FW)pump (Reciprocating)
5. FW heat exchanger
6. FW surge tank (Recip.)
7. Intercoolers (Reciprocatimg)
8. Aftercoolers (Reciprocating)
11. Diaphragm control valve
12. FW thermostatic control valve (Reciprocating)

Direct Flow

1. Solenoid valves
2. Check valves
3. Diaphragm control valves (Seawater)
4. Thermostatic control valves (Fresh water)
5. Back pressure valves
6. Miscellaneous valves

System Integrity

1. Piping/hoses
2. Various component casings and housings
3. Miscellaneous valves
4. Various gaskets & seals

Lubrication

1. Oil sump
2. Oil filter
3. Oil pump
4. Check valve
5. Oil strainer

System Self Protection

1. First stage discharge high air temperature switch
2. Second stage discharge high air temperature switch
3. First stage high condensate level shutdown switch/probe
4. Second stage high condensate level shutdown switch/probe
5. Low oil pressure shutdown
6. Condensate drain timer relays
7. FW high temperature switch
8. Relief valves
9. Zinc anodes

Water Removal

1. Water separators
2. Chiller/dehydrators
3. Drain monitors
4. Solenoid drain valves
5. Condensate sump

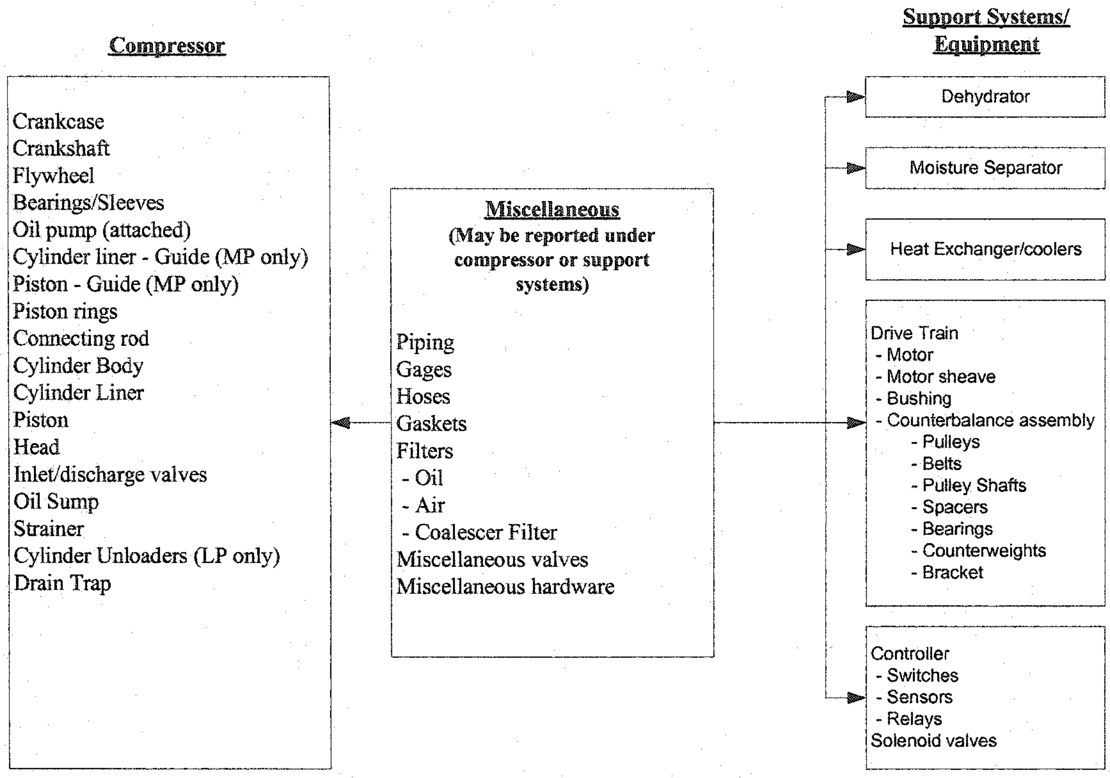
Air Compression

1. Compressor assembly
2. Belt Drive assembly
4. Drive motor
5. Motor controller
6. Unloading valve
7. Inlet filter /silencer

Sensing

1. Various sensors
    - Air discharge pressure
    - Heat exchanger pressure differential
    - Oil pressure
    - Crankcase oil temp
    - High FW cooling water temp
    - Sea water discharge temp
    - High air temperature
    - Cooling FW supply temp
    - Sea water inlet temperature
    - Moisture separator drain level (Reciprocating)
    - Dehydrator CondensateWater Level

Reciprocating (RCP) Compressor
Major Components



Appendix C

NPar Tests Platform A

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
RPNHIST - RPNEXP	Negative Ranks	52[a]	47.17	2453.00
	Positive Ranks	35[b]	39.29	1375.00
	Ties	0[c]		
	Total	87		

a. RPNHIST < RPNEXP

b. RPNHIST > RPNEXP

c. RPNEXP = RPNHIST

Test Statistics[b]

	RPNHIST - RPNEXP
Z	-2.282[a]
Asymp. Sig. (2-tailed)	.023

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

Sign Test

Frequencies

		N
RPNHIST - RPNEXP	Negative Differences[a]	52
	Positive Differences[b]	35
	Ties[c]	0
	Total	87

a. RPNHIST < RPNEXP

b. RPNHIST > RPNEXP

c. RPNEXP = RPNHIST

Test Statistics[a]

	RPNHIST - RPNEXP
Z	-1.715
Asymp. Sig. (2-tailed)	.086

a. Sign Test

NPar Tests

Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
RPNADJ - RPNHIST	Negative Ranks	28[a]	41.18	1153.00
	Positive Ranks	57[b]	43.89	2502.00
	Ties	2[c]		
	Total	87		

a. RPNADJ < RPNHIST

b. RPNADJ > RPNHIST

c. RPNHIST = RPNADJ

Test Statistics[b]

	RPNADJ - RPNHIST
Z	-2.956[a]
Asymp. Sig. (2-tailed)	.003

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Sign Test

Frequencies

		N
RPNADJ - RPNHIST	Negative Differences[a]	28
	Positive Differences[b]	57
	Ties[c]	2
	Total	87

a. RPNADJ < RPNHIST

b. RPNADJ > RPNHIST

c. RPNHIST = RPNADJ

Test Statistics[a]

	RPNADJ - RPNHIST
Z	-3.037
Asymp. Sig. (2-tailed)	.002

a. Sign Test

NPar Tests Platform B
Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
RPNHIST - RPNEXP	Negative Ranks	59[a]	49.00	2891.00
	Positive Ranks	25[b]	27.16	679.00
	Ties	3[c]		
	Total	87		

a. RPNHIST < RPNEXP

b. RPNHIST > RPNEXP

c. RPNEXP = RPNHIST

Test Statistics[b]

	RPNHIST - RPNEXP
Z	-4.933[a]
Asymp. Sig. (2-tailed)	.000

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

Sign Test

Frequencies

		N
RPNHIST - RPNEXP	Negative Differences[a]	59
	Positive Differences[b]	25
	Ties[c]	3
	Total	87

a. RPNHIST < RPNEXP

b. RPNHIST > RPNEXP

c. RPNEXP = RPNHIST

Test Statistics[a]

	RPNHIST - RPNEXP
Z	-3.601
Asymp. Sig. (2-tailed)	.000

a. Sign Test

NPar Tests
Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
RPNADJ - RPNH	Negative Ranks	13[a]	32.58	423.50
	Positive Ranks	62[b]	39.14	2426.50
	Ties	2[c]		
	Total	77		

a. RPNADJ < RPNH

b. RPNADJ > RPNH

c. RPNH = RPNADJ

Test Statistics[b]

	RPNADJ - RPNH
Z	-5.289[a]
Asymp. Sig. (2-tailed)	.000

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Sign Test

Frequencies

		N
RPNADJ - RPNH	Negative Differences[a]	13
	Positive Differences[b]	62
	Ties[c]	2
	Total	77

a. RPNADJ < RPNH

b. RPNADJ > RPNH

c. RPNH = RPNADJ

Test Statistics[a]

	RPNADJ - RPNH
Z	-5.543
Asymp. Sig. (2-tailed)	.000

a. Sign Test

NPar Tests Platform C
Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
RPNH - RPNE	Negative Ranks	55[a]	41.92	2305.50
	Positive Ranks	21[b]	29.55	620.50
	Ties	6[c]		
	Total	82		

a. RPNH < RPNE

b. RPNH > RPNE

c. RPNE = RPNH

Test Statistics[b]

	RPNH - RPNE
Z	-4.362[a]
Asymp. Sig. (2-tailed)	.000

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

Sign Test

Frequencies

		N
RPNH - RPNE	Negative Differences[a]	55
	Positive Differences[b]	21
	Ties[c]	6
	Total	82

a. RPNH < RPNE

b. RPNH > RPNE

c. RPNE = RPNH

Test Statistics[a]

	RPNH - RPNE
Z	-3.785
Asymp. Sig. (2-tailed)	.000

a. Sign Test

NPar Tests
Wilcoxon Signed Ranks Test

Ranks

		N	Mean	Sum of
RPNADJ -	Negative	20 [a]	41.18	1153.0
	Positive	57 [b]	43.89	2502.0
	Ties	5 [c]		
	Total	82		

a. RPNADJ <

b. RPNADJ >

c. RPNHIST =

Test Statistics[b]

	RPNADJ - RPNHIST
Z	-2.956[a]
Asymp. Sig. (2-tailed)	.003

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Sign Test

Frequencies

		N
RPNADJ - RPNHIST	Negative Differences[a]	28
	Positive Differences[b]	57
	Ties[c]	2
	Total	87

a. RPNADJ < RPNHIST

b. RPNADJ > RPNHIST

c. RPNHIST = RPNADJ

Test Statistics[a]

	RPNADJ - RPNHIST
Z	-3.037
Asymp. Sig. (2-tailed)	.002

a. Sign Test

NPar Tests Platform D
Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
RPNH - RPNE	Negative Ranks	58[a]	39.41	2286.00
	Positive Ranks	14[b]	24.43	342.00
	Ties	5[c]		
	Total	77		

a. RPNH < RPNE

b. RPNH > RPNE

c. RPNE = RPNH

Test Statistics[b]

	RPNH - RPNE
Z	-5.456[a]
Asymp. Sig. (2-tailed)	.000

a. Based on positive ranks.

b. Wilcoxon Signed Ranks Test

Sign Test

Frequencies

		N
RPNH - RPNE	Negative Differences[a]	58
	Positive Differences[b]	14
	Ties[c]	5
	Total	77

a. RPNH < RPNE

b. RPNH > RPNE

c. RPNE = RPNH

Test Statistics[a]

	RPNH - RPNE
Z	-5.068
Asymp. Sig. (2-tailed)	.000

a. Sign Test

NPar Tests
Wilcoxon Signed Ranks Test

Ranks

		N	Mean Rank	Sum of Ranks
RPNADJ - RPNH	Negative Ranks	13[a]	32.58	423.50
	Positive Ranks	62[b]	39.14	2426.50
	Ties	2[c]		
	Total	77		

a. RPNADJ < RPNH

b. RPNADJ > RPNH

c. RPNH = RPNADJ

Test Statistics[b]

	RPNADJ - RPNH
Z	-5.289[a]
Asymp. Sig. (2-tailed)	.000

a. Based on negative ranks.

b. Wilcoxon Signed Ranks Test

Sign Test

Frequencies

		N
RPNADJ - RPNH	Negative Differences[a]	13
	Positive Differences[b]	62
	Ties[c]	2
	Total	77

a. RPNADJ < RPNH

b. RPNADJ > RPNH

c. RPNH = RPNADJ

Test Statistics[a]

	RPNADJ - RPNH
Z	-5.543
Asymp. Sig. (2-tailed)	.000

a. Sign Test

Appendix D

Platform A

Best Subsets Regression: RPN versus Severity, Occurrence, Repair

```
Response is RPN

                                                S O
                                                e c
                                                v c R
                                                e u e
                                                r r p
                                                i r a
                                                t e i
Vars   R-Sq   R-Sq(adj)        C-p          S   y n r

   1   53.4         52.8    331.0    25.049         X
   1   28.1         27.2    553.2    31.119       X
   2   86.4         86.0     43.5    13.628       X X
   2   58.4         57.4    288.9    23.810     X   X
   3   91.1         90.8      4.0    11.078     X X X
```

Regression Analysis: RPN versus RXO-E

```
The regression equation is
RPN = - 4.31 + 5.67 RXO-E

Predictor        Coef     SE Coef          T        P
Constant       -4.305       1.737      -2.48    0.015
RXO-E          5.6663      0.1398      40.54    0.000

S = 7.907       R-Sq = 95.4%     R-Sq(adj) = 95.3%

Analysis of Variance

Source            DF          SS          MS         F         P
Regression         1      102730      102730   1643.12     0.000
Residual Error    80        5002          63
Total             81      107732
```

Regression Analysis: RPNadj versus RXO-A

```
The regression equation is
RPNadj = - 1.80 + 5.46 RXO-A

Predictor        Coef     SE Coef          T        P
Constant       -1.797       1.337      -1.34    0.183
RXO-A         5.46349     0.09716      56.23    0.000

S = 7.558       R-Sq = 97.5%     R-Sq(adj) = 97.5%

Analysis of Variance

Source            DF          SS          MS         F         P
Regression         1      180639      180639   3162.00     0.000
Residual Error    80        4570          57
Total             81      185209
```

Platform B
Best Subsets Regression: RPNE versus SevE, OccrE, RepE

```
Response is RPNE

                                                   O
                                                 S c R
                                                 e c e
                                                 v r p
Vars  R-Sq  R-Sq(adj)      C-p         S         E E E

   1  54.5       53.9    282.7    16.349             X
   1  34.3       33.5    444.9    19.641         X
   2  80.7       80.2     74.0    10.707           X X
   2  63.8       62.9    209.9    14.667         X   X
   3  89.7       89.3      4.0    7.8817         X X X
```

Regression Analysis: RPNE versus RxO E

```
The regression equation is
RPNE = - 4.30 + 3.68 RxO E

Predictor        Coef     SE Coef          T        P
Constant       -4.295       1.673      -2.57    0.012
RxO E          3.6773      0.1372      26.79    0.000

S = 7.884             R-Sq = 89.4%          R-Sq(adj) = 89.3%
PRESS = 5596.52       R-Sq(pred) = 88.79%

Analysis of Variance

Source           DF          SS          MS        F        P
Regression        1       44620       44620   717.91    0.000
Residual Error   85        5283          62
  Lack of Fit    14        1352          97     1.74    0.066
  Pure Error     71        3931          55
Total            86       49902
```

Regression Analysis: RPNadj versus RXO-A

```
The regression equation is
RPNadj = - 0.750 + 3.36 RXO-A

Predictor        Coef     SE Coef          T        P
Constant      -0.7505      0.6143      -1.22    0.223
RXO-A         3.36161     0.04775      70.40    0.000

S = 7.016             R-Sq = 93.4%          R-Sq(adj) = 93.4%
PRESS = 17676.9       R-Sq(pred) = 93.23%

Analysis of Variance

Source           DF          SS          MS        F        P
Regression        1      243947      243947  4956.33    0.000
Residual Error  352       17325          49
  Lack of Fit    13        6063         466    14.04    0.000
  Pure Error    339       11262          33
Total           353      261272
```

Platform C
Best Subsets Regression: RPN versus Severity, Occurrence, Repair

```
Response is RPN

                                                S O
                                                e c
                                                v c R
                                                e u e
                                                r r p
                                                i r a
                                                t e i
Vars  R-Sq  R-Sq(adj)        C-p         S      y n r

   1  55.7         55.2    268.1    16.021          X
   1  33.5         32.7    443.8    19.625  X
   2  80.7         80.3     71.6    10.627    X X
   2  64.0         63.2    204.1    14.523  X   X
   3  89.5         89.1      4.0    7.8834  X X X
```

Regression Analysis: RPN versus RXO-E

```
The regression equation is
RPN = - 4.29 + 3.66 RXO-E

Predictor         Coef   SE Coef          T       P
Constant        -4.294     1.661      -2.59   0.011
RXO-E           3.6629    0.1367      26.80   0.000

S = 7.830       R-Sq = 89.4%     R-Sq(adj) = 89.3%

Analysis of Variance

Source            DF          SS          MS         F         P
Regression         1       44031       44031    718.14     0.000
Residual Error    85        5212          61
Total             86       49242
```

Regression Analysis: RPNadj versus RXO-A

```
The regression equation is
RPNadj = - 1.89 + 3.48 RXO-A

Predictor         Coef   SE Coef          T       P
Constant        -1.885     1.274      -1.48   0.143
RXO-A          3.48136   0.09477      36.74   0.000

S = 7.469       R-Sq = 94.1%     R-Sq(adj) = 94.0%

Analysis of Variance

Source            DF          SS          MS         F         P
Regression         1       75284       75284   1349.52     0.000
Residual Error    85        4742          56
Total             86       80026
```

Platform D

Best Subsets Regression: RPN versus Severity, Occurrence, Repair

```
Response is RPN

                                                S O
                                                e c
                                                v c R
                                                e u e
                                                r r p
                                                i r a
                                                t e i
Vars   R-Sq    R-Sq(adj)        C-p         S   y n r

   1   54.4         53.8      296.6    25.345       X
   1   27.3         26.4      516.6    32.011     X
   2   86.3         85.9       40.5    14.015     X X
   2   59.4         58.3      258.7    24.100   X   X
   3   91.0         90.6        4.0    11.417   X X X
```

Regression Analysis: RPN versus RXO-E

```
The regression equation is
RPN = - 4.26 + 5.67 RXO-E

Predictor        Coef     SE Coef          T        P
Constant       -4.261       1.828      -2.33    0.022
RXO-E          5.6732      0.1453      39.04    0.000

S = 8.132       R-Sq = 95.3%     R-Sq(adj) = 95.2%

Analysis of Variance

Source            DF          SS          MS        F        P
Regression         1      100807      100807  1524.45    0.000
Residual Error    75        4960          66
Total             76      105767
```

Regression Analysis: RPNadj versus RXO-A

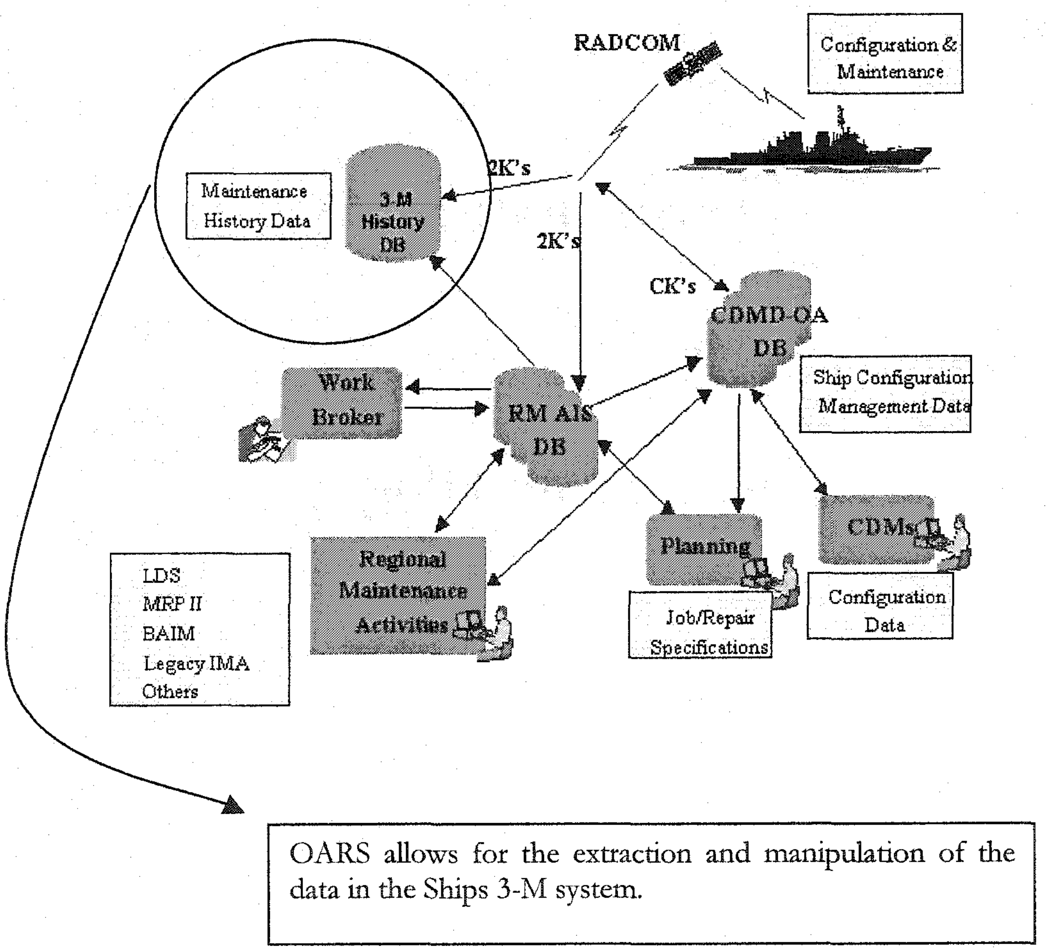
```
The regression equation is
RPNadj = 6.03 + 2.41 RXO-A

Predictor        Coef     SE Coef          T        P
Constant        6.026       2.425       2.48    0.015
RXO-A          2.4135      0.1633      14.78    0.000

S = 14.92       R-Sq = 74.4%     R-Sq(adj) = 74.1%

Analysis of Variance

Source            DF          SS          MS        F        P
Regression         1       48642       48642   218.39    0.000
Residual Error    75       16705         223
Total             76       65347
```

Appendix E

Compiling the Historical Data for Comparison

Development of the Historical Data used to create a Historical RPN Comparative was developed through the COMNAVSURFLANT effort. The results of the development of the Historical Data for the LP-MPAC are synopsized from internal COMNAVSURFLANT documents (LP-MP Failure Mode Report, August 2002). Information from that report appears here in abridged form for research consistency and military classification purposes.

Using the Open Architecture Retrieval System (OARS), the Data Analyst performed a search query to extract maintenance actions (OPNAV 4790/2Ks) for the past 5 years.



OARS allows for the extraction and manipulation of the data in the Ships 3-M system.

Figure 11, Maintenance Data Flow

The database selected was Ship's 3-M and the standard reports used were AD015 (All Maintenance Actions Plus Narrative) and AD08 (Maintenance Issues). Due to the varied nature of reporting maintenance data on LP and MP compressed air plants, it was necessary to cast a wide net to ensure all data was captured. Search queries were performed not only on SWLINs 55152 and 55153 (Compressors, MP air and LP air respectively), but also on SWLINs 55120 and 55121 (Air system, LP and MP). Table 7 displays the fields and entries used to perform these search queries. In the table, "H" is the TYCOM code for COMNAVSURFLANT. Both open and close ESWBS records were queried due to ESWBS usually resident on at least one of them.

Table 7, Search Query Fields (3-M OARS) Search Fields

Expression 1	Operator	Expression 2	Logical Operand
(TYCOM_CODE	=	H)	AND
(DATE_OPENING	BETWEEN	01/01/1997 to 03/01/2002)	AND
(ESWBS_OPENING	=	55153	OR
ESWBS_CLOSING	=	55153	OR
ESWBS_OPENING	=	55121	OR
ESWBS_CLOSING	=	55121	OR
ESWBS_OPENING	=	55152	OR
ESWBS_CLOSING	=	55152	OR
ESWBS_OPENING	=	55120	OR
ESWBS_CLOSING	=	55120)	

The result was all 3-M maintenance data associated with COMNAVSURFLANT LP/MP air compressors, which included some items not within the study boundaries. To refine the data, a word search query was accomplished to isolate only those maintenance actions of interest within the original data download. The following 95 key words (associated with low and medium air plants) were used in varied combinations to further electronically isolate the data of interest for the study:

1. Air Cylinder
2. Belt
3. Bearing
4. Compressor
5. Cooler
6. Cylinder (Head)
7. Cooler (Intercooler)
8. Cylinder (Liner)
9. Cooler (Lube)
10. Condenser
11. Coupling
12. Connecting Rod
13. Crankshaft
14. Controller
15. Cooling Water System (Including Coolers)
16. Dehydrator
17. Dehydrator (Refrig. Type)
18. Drain Trap
19. Expansion Tank
20. Filter (Air) & Breather
21. Filter/Strainer (Injection water)
22. Filter (Lube Oil)
23. Flow Switch
24. Float Switch
25. Float switch (Condensate)
26. Float Switch (Injection Sys)
27. Filter (Unloader)
28. Filters (Various)
29. Flywheel
30. Gasket
31. Gauge (Hour - Run Meter)
32. Gauge (Pressure)
33. Gauge (Temperature)
34. Gauge (Inj. Water Pressure)
35. Hose
36. Heat Exchanger (Fresh/SW)
37. Head Gasket
38. Head (High Pressure Assy)
39. Hold tank/separator
40. Indicators
41. Motor
42. Moisture Separator
43. Piston
44. Pulley
45. Pump (Oil)
46. Piping
47. Piston (ring)
48. Pressure Switch (Air)
49. Pressure Switch (Oil)
50. Pressure Switch (Injection water)
51. Pump
52. Fresh Water Pump
53. Pressure Transducer
54. Relay
55. Rod Packing
56. Rotor
57. Sump
58. Silencer/Muffler
59. Seal (Mechanical)
60. Seal (O-ring)
61. Sump Strainer
62. Strainer (Seawater)
63. Sensor (temperature
64. Switches
65. Timing Gear
66. Timer
67. Timer Relays
68. Temperature Switch (Air)
69. Temperature Switch (Dew Pt)
70. Temperature Switch (water)
71. Unloader Arm
72. Valve Backpressure
73. Valve (Check)
74. Salt Water System Cooling Valves
75. Valve Assembly (LP Discharge)
76. Valve (Receiver Drain)
77. FW Fill Valve
78. Valve (Injection System Drain)
79. Priority Valve
80. Valve (Relief)
81. Valve (root)
82. Valve Assembly (LP Suction)
83. Valve (Solenoid, Condensate Drn)
84. Valve (Solenoid tank Drain)
85. Valve (Solenoid Injection)
86. Valve (Solenoid Valve relay)
87. Unloader Valve Solenoid
88. Valve (SW Diaphragm control)
89. Valve (Thermostat Controlled)
90. Valve (Unloader)
91. Valve (Water Regulating)
92. Wiper Box
93. Water Lube Oil
94. Crosshead
95. Zinc Anodes

The 3-M OARS download and electronic sorting resulted in a total of 12,185 maintenance actions for low-pressure air plants [over five years] and a total of 2,269 maintenance actions for medium pressure air plants [also over five years]. The raw maintenance and cost data from each OPNAV 4790/2K was reviewed for applicability to ensure the components were inside the system study boundaries.

For purposes of analysis, it became necessary to specify which components were part of the "compressor" and which were part of supporting systems/components within the LP and MP Air Plant System. Failures for several miscellaneous components or consumables are applicable to both compressor and support equipment APLs. Therefore, for this situation, the gauge, filter, valve, gasket, etc., reported under an equipment/component APL was assumed to be part of the equipment/component under which it was reported. However some of these components have their own APL and not attributed to a specific component. When this occurs, the component is accounted for under it's own APL.

The data was then modeled to yield probability of failure over 12-month period in the COMNAVSURFLANT effort. This data was provided for use in the historical RPN comparative.

Additionally, the Navy has a Casualty Reporting (CASREP) system, where unit commanders report mission degradation of their ships to higher-level commanders. This is a classified report that is retained in a database. By removing the ship names and mission specifics, CASREP data becomes unclassified and can be analyzed. LPAC/MPAC CASREP data was gathered from the Navy consolidated CASREP reporting system for analysis in the COMNAVSURFLANT effort.

The vast majority of CASREPs were C-2 level, indicating minor mission effects (mostly due to redundancies in design) when one LPAC/ MPAC was lost. However, the much lower population MPACs showed more C3/C4 CASREPs than LPACs, indicating loss of a single MPAC has significant mission effects in some cases. This is probably due to the lack of an H.P. Air system back up in MPAC ships.

The data was then modeled to yield effect of failure on mission impact in the COMNAVSURFLANT effort. This data was provided for use in the historical RPN comparative.

The current maintenance strategies and tasks associated with low and medium pressure air plants were found in the MAI, ICMP and PMS and are detailed as follows:

MAI (Master Assessment Index) – The COMNAVSURFLANT Master Assessment Index (MAI) - accessible via the COMNAVSURFLANT web page - lists the maintenance objects assessed during SEMAT. The MAI provides a list of maintenance tasks and either the next scheduled assessment date or the most recently completed assessment date. (As the MAI database matures it is expected that both dates will be provided). The SEMAT tasks incorporate thirteen tasks under the following ESWBSs: 55152 (Compressors, MP Air) and 55153 (Compressors, LP Air).

ICMP –The current ICMP maintenance strategy for low and medium pressure air plant incorporates 13 tasks under the ESWBS 55121 (Air System, Low and Medium Pressure), 55152 (Compressors, MP Air) and 55153 (Compressors, LP Air).

PMS –The PMS tasks for low and medium pressure air plants incorporates the 85 tasks under the following Ship Work Authorization Boundary (SWAB) number 5510 (Compressed air systems) 5515 (Compressors, Air)

In addition to the ICMP, PMS and MAI, the following sources were reviewed for maintenance requirements as they pertain to low and medium air pressure air plants: Naval Ships Technical Manual (NSTM), Joint Fleet Maintenance Manual (JFMM), Engineering for Reduced Maintenance (ERM) and Cumbersome Work Packages (CWP).

The COMNAVSURFLANT effort was able to derive a comparative nominal numeric score for the level of repair necessary to repair the system in the event of failure. The data was provided for use in the research.

The data yielding from this filtration, verification and validation of the data resulted in statistical data that, when applied to a FMEA model, produced a practical numeric comparison that may be used to substantiate the expert solicitation FMEA model proposed in the research.

CURRICULUM VITA

FOR

ANTHONY W. DEAN

Professional History:

- Visiting Assistant Professor of Engineering Technology, Old Dominion University, Norfolk, VA 2001-present
- Adjunct Instructor, Department of Engineering Management, Old Dominion University, Norfolk, VA 2000-2001
- Director of Business Development, Clark-Smith Associates, P.C., Norfolk, VA 1999-2001
- Mechanical Engineer, Clark-Smith Associates, P.C., Norfolk, VA 1997-1999
- General Manager, Nickelese Corporation, Norfolk, VA, 1993-1997
- Operations Manager, Art-Mark Inc., Virginia Beach, VA.1991-1993
- Nuclear Propulsion Plant Operator – Electrical, U.S. Navy, Norfolk, VA. 1984-1991

Education:

- Old Dominion University, Doctor of Philosophy, Engineering Management, 2003
- College of William and Mary, Master of Business Administration, 2000
- Old Dominion University, Bachelor of Science Mechanical Engineering Technology, 1998
- U.S. Navy Schools Completed, 1984-1991
    - Leadership and Management Education and Training
    - U.S. Naval Nuclear Submarine Prototype Training, SIC
    - U.S. Naval Nuclear Power School
    - U.S. Navy Electrician's Mate "A" School
    - U.S. Navy Basic Electronics and Electricity School

Research Activity:

- AMSEC LLC, "Ship Repair Decision Model Feasibility Study", co-PI, ($5000) 2002
- AMSEC LLC, Decision Support System for Maintenance Assessment, co-PI, ($30,000) 2002
- AMSEC LLC, Decision Support System for Maintenance Assessment Phase II, PI, ($30,000) 2003

Consulting (Private Industry):

- CONOCO/Columbia Propane Corporation
- Siemens Automotive
- Anhueser-Busch, Inc. - Williamsburg
- Mitsubishi Chemicals America
- American Waste Industries
- ABB – Saudi Arabia
- Newport News Shipbuilding
- Yupo
- Southeastern Public Service Authority
- Ciba Specialty Chemicals
- Howmet Castings

Scientific and Professional Society Membership:

- American Society of Naval Engineers
- American Society of Mechanical Engineers
- American Society of Engineering Management
- Phi Kappa Phi