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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**A SYSTEM OF SYSTEMS INTERFACE HAZARD
ANALYSIS TECHNIQUE**

by

Patrick Redmond

March 2007

Thesis Co-Advisors:

J. Bret Michael
Paul Shebalin

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REPORT DOCUMENTATION PAGE			<i>Form Approved OMB No. 0704-0188</i>
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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE March 2007	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE A System of Systems Interface Hazard Analysis Technique		5. FUNDING NUMBERS	
6. AUTHOR(S) Patrick Redmond		8. PERFORMING ORGANIZATION REPORT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000		10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A		11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.	
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.		12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) The next generation of military capabilities will hinge on systems of systems technologies, entailing the integration of numerous large scale systems into a complex system of systems whose capability exceeds the capabilities of the individual systems. The increase in capability is due to the emergent properties of the system of systems. However, these emergent properties also introduce hazards that must be adequately dealt with before the system of systems can be employed. The current state of hazard analysis processes is insufficient to deal with the complexity and size of a system of systems. This thesis aims to define the nature and types of hazards associated with systems of systems and to define a technique for identifying specific hazards within a system of systems. In addition to developing a theoretical process, this thesis applies it to a real world case study, the Ballistic Missile Defense System. A software application was developed to prove the concept of the hazard analysis technique. The technique has been designed from the top down to be compatible with current system safety processes and as such, is directly compatible with systems of systems currently in development and familiar to practicing system safety engineers.			
14. SUBJECT TERMS Systems of Systems, System Safety, System Hazard Analysis, Emergent Hazards		15. NUMBER OF PAGES 151	16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

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A SYSTEM OF SYSTEMS INTERFACE HAZARD ANALYSIS TECHNIQUE

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Submitted in partial fulfillment of the
requirements for the degrees of

**MASTERS OF SCIENCE IN SOFTWARE ENGINEERING
and
MASTERS OF SCIENCE IN SYSTEMS ENGINEERING**

from the

**NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The next generation of military capabilities will hinge on systems of systems technologies, entailing the integration of numerous large-scale systems into a complex system of systems whose capability exceeds the capabilities of the individual systems. The increase in capability is due to the emergent properties of the system of systems. However, these emergent properties also introduce hazards that must be adequately dealt with before the system of systems can be employed. The current state of hazard analysis processes is insufficient to deal with the complexity and size of a system of systems. This thesis aims to define the nature and types of hazards associated with systems of systems and to define a technique for identifying specific hazards within a system of systems.

In addition to developing a theoretical process, this thesis applies hazard analysis to a real-world case study, the Ballistic Missile Defense System. A software application was developed to prove the concept of the hazard analysis technique. The technique has been designed from the top down to be compatible with current system safety processes and as such, is directly compatible with systems of systems currently in development and familiar to practicing system safety engineers.

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ACKNOWLEDGMENTS

I'd like to thank the Royal Australian Air Force for providing me the opportunity to pursue full time study. These opportunities are rare and costly and I appreciate the privilege.

I'd also like to thank my advisors, Prof. Bret Michael and Prof. Paul Shebalin. Their guidance has been invaluable. I greatly appreciate their flexibility in reviewing this work so close to the deadline. Without their guidance and contributions, this thesis would not have been possible.

Finally, I'd like to thank Miss Cheryl Emmons for supporting me through the long nights of research, drafting and coding and for taking care of the things this work caused me to neglect. Thank you for your understanding, patience and support.

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I. INTRODUCTION

A. OVERVIEW

There are currently several large, high-profile Department of Defense acquisition programs that are seeking to develop systems of systems to address mission needs that might otherwise prove impossible to support. A system of systems is an integrated set of systems that uses each system in a coordinated fashion to achieve a mission that the individual systems cannot achieve on their own. The Ballistic Missile Defense System (BMDS) and the U.S. Army's Future Combat System (FCS) are example of systems of systems. These systems of systems are extremely large, complex and hazardous. They employ interdependencies that further complicate systems operation. A responsible employment of a system of systems requires a system safety program that ensures that the risk of employment is tolerable.

However, system hazard analysis techniques are unable to cope with the size or complexity of systems of systems. In addition to being a collection of large scale systems, a system of systems is also able to dynamically reconfigure, which results in virtually endless system of systems states and configurations. New hazard analysis techniques are required to deal with systems of systems. These techniques must be capable of handling the large scale of a system of systems and produce meaningful results while remaining economically practical.

In Chapter II, the background to the issue is provided, including the characteristics of systems of systems that render most hazard analysis technique ineffective and the requirements that any new hazard analysis technique must meet. It is here that the problem to be resolved is fully defined.

Chapter III identifies and defines the types of systems of systems hazards. It breaks the full set of hazards down into subcategories that can be more manageably addressed. The large scale of systems of systems, and the potentially large number of hazards means that the analysis must be subdivided

into manageable pieces. This chapter provides the means for doing so by subdividing the full set of hazards into coherent hazard types that can be addressed individually.

In Chapter IV, a hazard analysis technique is defined to address a specific type of system of systems hazard. This technique will meet the requirements outlined in Chapter II. Namely, it must be effective, practical and compatible with other hazard analysis techniques.

The hazard analysis technique defined in Chapter IV will be applied to the Ballistic Missile Defense System in Chapter V as a case study. The purpose of this case study is to validate the effectiveness of the hazard analysis technique.

B. OBJECTIVES

The objectives of this thesis are to:

- (i) identify and define the nature of systems of systems hazards,
- (ii) define a technique that can be used to identify and analyze a specific type of system of systems hazard, and
- (iii) apply this technique to a case study to demonstrate the concept.

II. BACKGROUND

A. INTRODUCTION

Perhaps the highest profile, most controversial and most expensive Defense program is the Ballistic Missile Defense System, which uses a large number of current and developmental systems in a network centric environment in order to destroy ballistic missiles in flight. The BMDS is a system of systems, as is the U.S. Army's FCS. These systems of systems are both highly complex and hazardous.

A system of systems is built on systems technology. A system is in itself a complex entity. The Ballistic Missile Defense System utilizes the Aegis system, which is one of the most complex weapon systems ever acquired by the United States Navy. Integration of such a system into a complex network of systems only adds to the overall complexity of the BMDS.

In addition to being highly complex, a system of systems can also be hazardous. In fact, all of the mishaps that are possible within the systems are also possible within the system of systems, but there are many new causes. In order to ensure that the deployed system of systems is safe to operate, a technique must be developed to identify the new hazards.

This chapter provides the background information necessary for the research that follows. It will describe the basics of systems and systems of systems technology, as well as the issues associated with system safety. The system of systems hazard analysis problem will be described, and the questions to be answered defined.

B. SYSTEMS

1. Overview

The concept of a system is relatively new. Systems have only been purpose-built since the middle of the twentieth century. However, there are some examples of systems from the early twentieth century though they were not thought of as systems at the time of their creation. As knowledge of science and

engineering rapidly expanded in the post-war period, engineers sought to take advantage of the old adage “the whole is greater than the sum of the parts”. That is, to integrate several disciplines and technologies in order to achieve a goal that could not be achieved without cooperation. What they sought to develop was a system, “a construct or collection of different elements that together produce results not obtainable by the elements alone.”¹

Systems have characteristics that set them apart from components, units and other products of engineering processes. The IEEE defines a system as:

[a] set or arrangement of elements [people, products (hardware and software) and processes (facilities, equipment, material and procedures)] that are related and whose behavior satisfies operational needs and provides for the life cycle sustainment of the products.²

From this, it is clear that the characteristics of a system include, but are not limited to, a purpose, integrated components and a life cycle.

2. Characteristics of a System

a. Purpose

Man-made systems are constructed to fulfill a specific purpose. Systems are expensive and time consuming to develop and should only be developed with a specific purpose in mind. In fact, the systems engineering process requires that a purpose or role either be known or obtainable.³

b. Integrated Components

A system is not merely a product that fulfills a purpose. A system utilizes multiple disciplines and technologies to achieve its purpose. Subsystems and components are used to harness each of these disciplines. The first products to be engineered as systems were the early generation intercontinental ballistic missiles (ICBM). The ICBM utilizes liquid or solid fuel rockets, an aerodynamic

¹ *A Consensus of the INCOSE Fellows* Retrieved February 27, 2007 from <http://www.incose.org/practice/fellowsconsensus.aspx>.

² IEEE 1220-2005 *Standard for Application and Management of the Systems Engineering Process* (2005) §3.1.34.

³ *Ibid.*, §5.1.1.

case with control surfaces, electronic guidance equipment and the warhead. Not only are each of these subcomponents highly integrated, they are also highly complex in their own right.

c. Life Cycle

A system exists for a life cycle. That is, it is conceived, developed, produced, used and disposed. Not only does this require a system be designed to survive for a long life cycle (e.g. greater than fifty years for the B-52), but support systems have to be developed. A system is more than the obvious. It includes all of the support systems, procedures, documentation, data and personnel required to support it through a full life cycle.

C. SYSTEMS OF SYSTEMS

1. Overview

The natural evolution from systems development was to integrate several systems into a system of systems. The system of systems concept has taken a high profile in recent years due to some large-scale, high-priority Defense programs that employ the technology, in particular, the BMDS and FCS. These systems of systems take established systems, each with their own purpose and with a certain level of autonomy, and attempt to integrate them in order to achieve capabilities and both levels of performance and dependability that the individual systems cannot achieve on their own. A system of systems is

an amalgamation of legacy systems and developing systems that provide an enhanced military capability greater than any of the individual systems within the system of systems.⁴

Systems of systems share some characteristics with systems, but there are a number of characteristics which distinguish them, and which can lead to increased effort through the integration process. Like systems, a system of systems is integrated in order to meet a need or to fulfill a purpose and the system of systems will exhibit behaviors not present in any of the systems alone. However, unlike systems, a system of systems is exponentially more complex.

⁴ D.S. Caffal, and J.B. Michael (2005). Architectural Framework for a System-of-Systems *IEEE International Conference on Systems, Man and Cybernetics*, pp. 1876-1881.

The difference is so significant that systems of systems development is not merely a larger version of systems development, but rather a new problem altogether. Also, subsystems that are integrated to form a system are unable to perform functions individually and are most likely unable to even operate on their own. This is not the case for a system of systems, where the systems that make up the system of systems are all capable of operating on their own and performing functions that may be related to the purpose of the system of systems.

There are a large number of characteristics of a system of systems, more than will be discussed here. The characteristics that are discussed here are those that have a direct influence on the safety of systems of systems.

2. Characteristics of a System of Systems

a. Complexity

Systems are complex. It logically follows that an integrated set of systems will be more so. Systems of systems employ complex interactions and dependencies between complex systems and as such, the complexity of a system of systems is exponentially greater than the complexity of a system. Systems may enter and leave the system of systems, may perform different roles, may be connected to one system and not another and then vice versa. The states of a system of systems are virtually infinite. This complexity means that new analysis techniques are required to manage the sheer size of the problem.⁵

b. Emergent Behavior

A system of systems can perform functions that the component systems alone cannot achieve. The difference between what the systems can achieve individually and what the system of systems can achieve is termed emergent behavior.⁶ While some emergent behaviors are the desired effect of creating a system of systems, they can also cause problems. Some emergent

⁵ G. Despotou, R. Alexander, and M. Hall-May (2003). *Key Concepts and Characteristics of Systems of Systems*, Technical Report DARP/BG/2003/1, University of York, §3.4.

⁶ *Ibid.*, §3.7.

behaviors are intentional, others are not. Unintended emergent behaviors can have significant consequences and efforts must be made to ensure that the consequences are minimized.⁷

c. *Autonomy*

A system is constructed of components that are unable to operate on their own, and even if they could, they would not fulfill a useful purpose. In contrast, a system of systems is constructed of systems that operate on their own on a regular basis and are able to perform functions independently that may be unrelated to the functions of the system of systems.⁸

D. HAZARDS

1. Overview

There is risk associated with the operation of systems and systems of systems. The risk is associated with the hazards present in the system or system of systems. When dealing with systems, the terminology used by engineers to describe risk can have meanings that are contrary to the common usage of the terms in other contexts. What follows is an overview of the most important terms.

2. Terminology

a. *Failure*

A failure is an instance of a system, unit or component not operating as designed. Failures may be overt (that is, the effects may be known to operators or other system components) or insidious (that is, the effects of the failure are not detected).

b. *Fault*

A fault is a design or manufacturing flaw that exists within a system or component that may or may not have caused a failure. Faults may be present within a system for extended periods of time before manifesting as a failure. For example, a crack in a metal brace is a fault. It becomes a failure when the crack grows to the size where the brace breaks.

⁷ G. Despotou, R. Alexander, and M. Hall-May (2003). *Key Concepts and Characteristics of Systems of Systems*, Technical Report DARP/BG/2003/1, University of York, §3.7.

⁸ *Ibid.*, §3.1.

c. Mishap

A mishap, or accident, is an event that causes injury or death to personnel, loss or damage to property, or damage to the environment.⁹ Most systems control or produce some form of energy. A mishap is an uncontrolled release of that energy. For example, a nuclear meltdown is an uncontrolled release of nuclear energy and is a mishap associated with a nuclear power plant. An aircraft crash is the uncontrolled release of the potential energy associated with being at altitude. However, not all uncontrolled releases of energy are mishaps. The release must cause damage. An uncontrolled release of energy that does not cause damage is a 'near miss' and may have, under different circumstances, caused damage.¹⁰ When defining a mishap, the type of energy release and the victim (personnel, property or the environment) must be defined. The conditions that lead to the mishap are not part of the mishap definition. Instead, they form part of the hazard definition.

d. Hazard

Hazard is a term in common usage that has a different meaning within systems terminology. In common usage, a hazard is a potential danger. For example, in golf, a hazard is a sand bunker or water feature that the player wishes to avoid. Within systems terminology, a hazard is more than just the potential danger. A full description of a hazard must also include the conditions that can lead to the mishap. A systems definition of a hazard within the golfing context would be that the ball is close enough to the hazard to induce the player into choosing to hit over it and that the ball does not make it over due to a significant head wind. A hazard is a set of conditions that may lead to a mishap, not just the potential danger. MIL-STD-882D defines a hazard as:

⁹ MIL-STD-882D *Standard Practice for System Safety* (2000) §3.2.6.

¹⁰ N. Leveson (1995). *Safeware: System Safety and Computers* Boston: Addison Wesley, p. 176.

[a]ny real or potential *condition* that can cause injury, illness or death to personnel; damage to or loss of a system, equipment or property; or damage to the environment. [emphasis added]¹¹

e. Hazard Causal Factor

A hazard causal factor is an event, condition, failure, fault or any other aspect that is a required for a hazard to occur.

f. Mishap Risk

Mishap risk is a somewhat confusing term. By strict definition, mishap risk is:

[a]n expression of the impact and possibility of a mishap in terms of potential mishap severity and probability of occurrence.¹²

However, it is difficult to assign a probability of occurrence to a mishap alone. The hazards that can lead to that mishap must be known in order to know the conditions and events that lead to the mishap. It is the conditions and events that have a probability of occurrence. The probability of occurrence of a mishap is a function of the probability of occurrence of the hazards that lead to the mishap. While it is possible to generate the probability of occurrence of a mishap from the hazards that lead to the mishap (and there are likely to be several hazards), it is more useful to leave the probability of occurrence at the hazard level. For example, a nuclear meltdown can occur either due to a control rod failure, or due to a failure of the pumps that circulate the coolant. The mishap is the nuclear meltdown, and the mishap probability is the probability that either the control rods fail or the pumps fail. To reduce the probability of a nuclear meltdown, you must address either the probability of control rod failure or the probability of pump failure.

As such, in general practice, a mishap risk is calculated for a hazard, not a mishap. The mishap risk (or hazard risk) is an expression of the severity of the mishap caused by the hazard and the probability of occurrence of the conditions that lead to the hazard.

¹¹ MIL-STD-882D *Standard Practice for System Safety* (2000) §3.2.3.

¹² *Ibid.*, §3.2.7.

g. Residual Mishap Risk

The residual mishap risk is the risk that exists in the fielded system.¹³ Once the hazards of a system have been identified, effort is made to ensure that each of these hazards is acceptable. The system design may be changed, or changes made to the operating procedure in an effort to reduce the probability or consequence of a hazard. Once all these efforts have been employed, there is still risk left in the system. This is the residual mishap risk. Residual mishap risk is an important concept as it is this risk that is accepted by the system operator or developer. In general, there is a threshold for residual mishap risk. Above a certain level, the risk of operating a system (the residual mishap risk) may not outweigh the benefits of operating the system.

E. SYSTEM SAFETY

1. Overview

Systems are inherently dangerous. Almost without exception, a system will control some type of dangerous force, be it electrical, chemical, potential or nuclear. Systems engineering focuses primarily on developing system performance and function, occasionally to the detriment of safety. System safety is a program that runs concurrently with systems engineering that aims to increase the safety of a system while still permitting system function. Systems safety engineering is a specialty on its own, and most defense acquisition programs require a system safety program by regulation. It is a complex discipline that can take substantial resources, but it has proven to increase the safety of deployed systems.¹⁴

¹³ MIL-STD-882D *Standard Practice for System Safety* (2000) §3.2.9.

¹⁴ N. Leveson (1995). *Safeware: System Safety and Computers* Boston: Addison Wesley, pp. 145-150.

2. Safety

MIL-STD-882D defines safety as:

[f]reedom from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment.¹⁵

For the most part, developing and employing a system involves exposure to these conditions. The only way of avoiding this is to avoid the system. For example, irrespective of how it is designed and built, there is always a chance that an aircraft will crash. Successful employment of a system involves not only recognizing the exposure (intentional or otherwise) to these conditions, but also employing active techniques to minimize the likelihood or impact of these conditions.

3. How Safe is Safe Enough?

There is risk in everything we do. Driving a motor vehicle is a particularly dangerous activity, and yet it is done by millions everyday. BASE jumping is also a particularly dangerous activity, but this activity is undertaken by far fewer people. The decision is based upon an assessment of risk versus reward or necessity. Driving a motor vehicle is an essential task, and hence the risks involved are readily undertaken. BASE jumping is not an essential task, and hence it is only undertaken by those who view the benefit of the thrill worth the risks involved. When dealing with systems, it is not possible to remove all risk. The point at which a system becomes safe enough is the point at which the benefit of the system outweighs the risks. This will vary not only with the type of system involved, but also on the role of the system. For example, military aircraft operations will accept much higher levels of risk during a time of conflict than during training exercises.

4. System Safety Objectives

According to Leveson, there are two system safety objectives: either to “make something safer,” or “to convince a government licensor that it is already

¹⁵ MIL-STD-882D *Standard Practice for System Safety* (2000) §3.2.10.

safe.”¹⁶ In many instances, there are government regulations that require the developer or operator of a system to conclusively demonstrate that a system meets a mandated safety level. For example, the Federal Aviation Administration mandates failure probability objectives for aircraft that operate within the United States. If it cannot be demonstrated that an aircraft type meets these objectives, then the aircraft cannot be operated. Alternatively, the developer of a system may employ system safety techniques in order to make its product safer, usually for economic reasons. For example, a developer of electronic products may choose to invest in a system safety program in the hope that it will reduce the cost of lawsuits due to accidents, or a car manufacturer may seek to make their vehicles safer in order to make them more attractive to consumers, and hence increase sales.

5. A System Safety Process

a. Overview

The system safety process is a specific application of the risk management process with the objective of increasing the safety of the system. Although there are numerous system safety standards, the variations to the core process are minimal. For the purpose of this research, the system safety process defined by MIL-STD-882D *Standard Practice for System Safety* will be used. This process is shown in Figure 1, and described below.

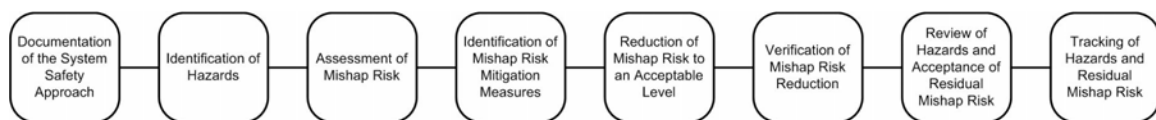


Figure 1. MIL-STD-882D System Safety Process

b. Documentation of the System Safety Approach

The system safety approach must be documented and approved by program authorities. The documentation must identify each hazard analysis and

¹⁶ N. Leveson (1995). *Safeware: System Safety and Computers* Boston: Addison Wesley, p. 152.

mishap risk assessment process to be used and must also indicate how the system safety program integrates into the overall system program. The documentation also defines how risks are communicated to and accepted by the appropriate authority and the method for tracking hazards and residual mishap risk.¹⁷

c. Identification of Hazards

Hazards must be identified through a systematic hazard analysis process. All aspects of the system must be considered, including the hardware, the software, the environment and the system purpose, over all phases of the system life cycle. Identification of hazards is a collaborative process that involves all program members.¹⁸

d. Assessment of Mishap Risk

Once each hazard has been identified, the probability that the hazard will occur and the consequence of occurrence must be determined. Probabilities may be determined qualitatively. When determining consequence, the effect on people, property and the environment must be considered. The probability and consequence can be combined into a mishap risk priority index.¹⁹

e. Identification of Mishap Risk Mitigation Measures

Measures that reduce the mishap risk must be identified for each hazard with an unacceptable risk level. Each of these measures should be assessed to determine its level of effectiveness in reducing mishap risk. In general, risks should be mitigated in accordance with the safety design order of precedence:²⁰

- (i) Eliminate hazards through design selection,
- (ii) Incorporate safety devices,
- (iii) Provide warning devices, and
- (iv) Develop procedures and training.

¹⁷ MIL-STD-882D. *Standard Practice for System Safety* (2000) §4.1.

¹⁸ *Ibid.*, §4.2.

¹⁹ *Ibid.*, §4.3.

²⁰ *Ibid.*, §4.4.

f. *Reduction of Mishap Risk to an Acceptable Level*

Once the most appropriate measures for mitigating mishap risk have been identified, the measures must be implemented. This may involve creating and adding safety requirements to the system specification, making changes to the system design or developing training procedures that avoid hazards.²¹

g. *Verification of Mishap Risk Reduction*

Any mishap risk reduction that has been performed must be verified by analysis, inspection or test in order to ensure that the desired effect has been achieved.²²

h. *Review of Hazards and Acceptance of Residual Mishap Risk*

At the completion of the mishap risk reduction activities, the appropriate authority must review the system hazards and accept the residual mishap risk. The residual mishap risk is the risk that remains once all mishap risk mitigation strategies have been employed. If the appropriate authority is unable to accept the residual mishap risk, further mishap risk reduction measures need to be employed.²³

i. *Tracking of Hazards and Residual Mishap Risk*

The hazards and residual mishap risk must be tracked as the system evolves throughout the life cycle. This includes updating probability assessments if they prove to be erroneous, adding or removing hazards as the system is modified and tracking closure actions to ensure they are completed.²⁴

F. SYSTEM HAZARD ANALYSES

1. Overview

The primary task within a system safety program is a hazard analysis. Hazard analyses can be performed at different times within the system life cycle, at different levels within the system design and for the purpose of identifying

²¹ MIL-STD-882D. *Standard Practice for System Safety* (2000) §4.5.

²² *Ibid.*, §4.6.

²³ *Ibid.*, §4.7.

²⁴ *Ibid.*, §4.8.

different types of hazards. A system safety program should be designed for a specific application, and is likely to include a number of different hazard analyses and several techniques for performing each hazard analysis. The most common hazard analysis is a system hazard analysis, which commences early in the life cycle (as soon as sufficient data is available for the relevant hazard analysis technique) and continues as the system evolves. A system hazard analysis deals with hazards at the system level (as opposed to the subsystem or unit level). There are a large number of system hazard analysis techniques, the most common of which are described below.

2. System Hazard Analysis Objectives

The purpose of a system hazard analysis is to identify and assess system-level hazards. System-level hazards are primarily hazards associated with the interfaces and interactions between subsystems, but may also include potentially safety-critical human errors.²⁵ There are a large number of techniques for conducting a system hazard analysis. Any system hazard analysis technique must not only be able to identify hazards in a cost-effective fashion, it must also employ a formal approach that either provides complete coverage of the system, or clearly identifies the aspects of the system that have not been analyzed. The choice of a system hazard analysis technique is application specific, and will depend upon the criticality and complexity of the system as well as the amount of system information that is available. Several commonly used system hazard analysis techniques are described below.

The primary output of a system hazard analysis is a system hazard analysis report. This report is effectively a list of all system hazards, including an assessment of the risk associated with each hazard and the recommended strategy for mitigating each hazard. An abridged example of a system hazard

²⁵ National Aeronautics and Space Administration. (1999). *System Safety Handbook* (DHB-S-001) Edwards, CA: Dryden Research Flight Center, p. 28.

analysis report is shown in Table 1. Any system hazard analysis technique must be able to populate such a table. The data to be included in the table is as follows:²⁶

- (i) **System/Subsystem/Unit.** List every system, subsystem and unit to be analyzed.
- (ii) **Component Failure Mode.** For each system, subsystem and unit, list all failure modes that can result in a hazard.
- (iii) **Hazard Description.** Describe the hazard that results from each component failure mode.
- (iv) **Effect of Hazard.** Determine the effect of each hazard in terms of the damage that the subsequent mishap may cause to personnel, property or the environment.
- (v) **Risk Assessment.** Determine the risk of each hazard in terms of severity and probability before any hazard mitigation activities have been conducted.
- (vi) **Recommended Action.** Identify the actions that must be taken in order to reduce the hazard risk to an acceptable level.
- (vii) **Effect of Recommended Action.** Determine the risk of each hazard once all hazard mitigation activities have been conducted.

(i) System/ Subsystem/ Unit	(ii) Component Failure Mode	(iii) Hazard Description	(iv) Effect of Hazard	(v) Risk Assessment	(vi) Recommended Action	(vii) Effect of Recommended Action
Control Rods	Actuator Fails	Control rod state becomes uncontrollable, reactor overheats.	Large scale loss of life	Catastrophic Remote	Implement fail safe design, control rods close on failure.	Marginal Remote
...

Table 1. Example System Hazard Analysis Report

3. System Hazard Analysis Techniques

a. Fault Tree Analysis

Fault Tree Analysis (FTA) is a top-down approach to identifying the causes of system hazards. The process requires knowledge of substantial

²⁶ Office of Management and Budget. (1995). *System Safety Hazard Analysis Report* (DI-SAFT-80101B) Washington, DC.

system detail, and cannot be performed completely early in the process (although it can be commenced and still prove fruitful), but does provide full system coverage, permits quantitative analysis and combinations of failures, and is very cost effective in identifying system hazards. An overview of the process is shown in Figure 2.

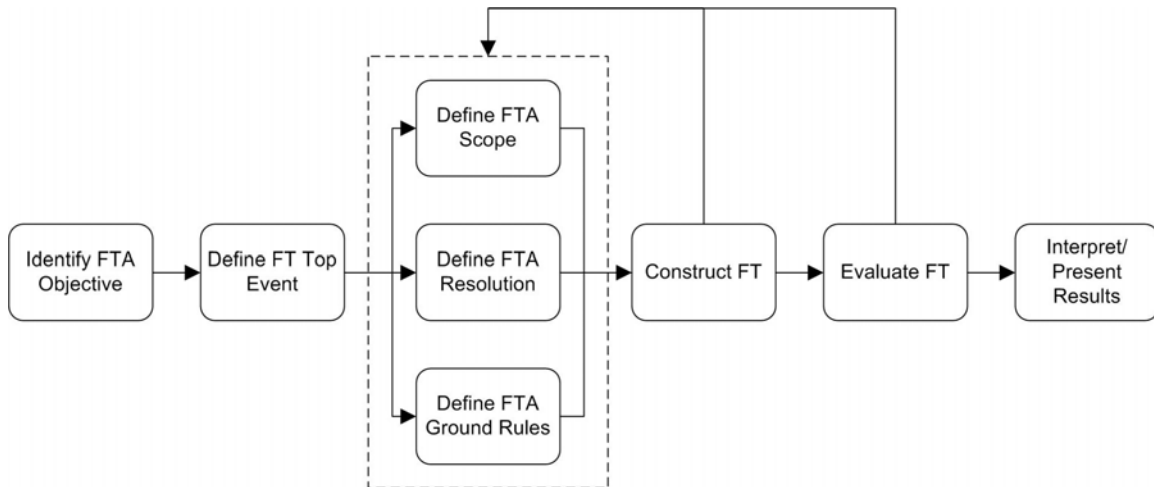


Figure 2. Fault Tree Analysis Process²⁷

The steps are as follows:

- (i) **Identify FTA Objective.** Establish the purpose of the analysis and the types of mishaps to be analyzed. The objective may be to determine the probability of a mishap occurring, or to determine the most effective method of reducing a mishaps probability.
- (ii) **Define Fault Tree (FT) Top Event.** Identify the system mishap to be analyzed within a specific fault tree. The fault tree will identify the causes and probability of the chosen mishap.
- (iii) **Define FTA Scope.** Determine which systems will be included as contributors to the system mishap, and which will be excluded, as well as the version of the system to be analyzed and the system boundary conditions such as initial states and input ranges.
- (iv) **Define FTA Resolution.** Determine the level to which the failure causes for the top event will be developed. The objective of the FTA may be achieved by developing the FT to the subsystem level, or it may require that the unit level be considered.

²⁷ From National Aeronautics and Space Administration. (2002). *Fault Tree Handbook with Aerospace Applications* (Version 1.1) Washington, DC: NASA Office of Safety and Mission Assurance, p. 22.

- (v) **Define FTA Ground Rules.** Establish a consistent method for naming FT events and gates.
- (vi) **Construct FT.** Starting with the top event, define the combination of lower level failures or events that will cause the top event to occur. If the top event is a system level mishap, the first level of failures will be at the subsystem level, the second level at the unit level and so on. Continue to decompose lower level events until the FTA objective can be achieved.
- (vii) **Evaluate FT.** Evaluate the FT qualitatively and quantitatively. A qualitative analysis will determine subsets of events that can cause the top event (not every event within a FT is required to cause the top event) and will identify events whose elimination will prevent the top event. A quantitative analysis can determine the overall probability of the top event and the probability of each of the subsets that cause the top event.
- (viii) **Interpret/Present Results.** Assess the importance of the FTA results and report them to the relevant decision maker.

An example fault tree is shown in Figure 3. The top event is the 'System Mishap'. The fault tree shows that the system mishap can be caused by either a combination of failures F_1 and F_2 , or by a combination of failures F_3 and F_4 . In order to prevent the system mishap, one of failures F_1 or F_2 and one of failures F_3 or F_4 must be prevented. Preventing failure F_1 alone does not prevent the system mishap. Depending upon the objective of the FTA, the FT may be further broken down. For example, failure F_4 may actually be the combination of several failures within the subsystem that exhibits failure F_4 .

Fault tree analysis is one of the most efficient system hazard analysis techniques. The process begins with a system mishap, and then expands upon the causes of that system mishap. Every step of the FTA is therefore guaranteed to provide further insight into a system mishap. This is not true of other system hazard analysis processes that do not employ the top down approach. With a bottom up approach, significant effort may be expended analyzing a subsystem failure that does not result in a system mishap.

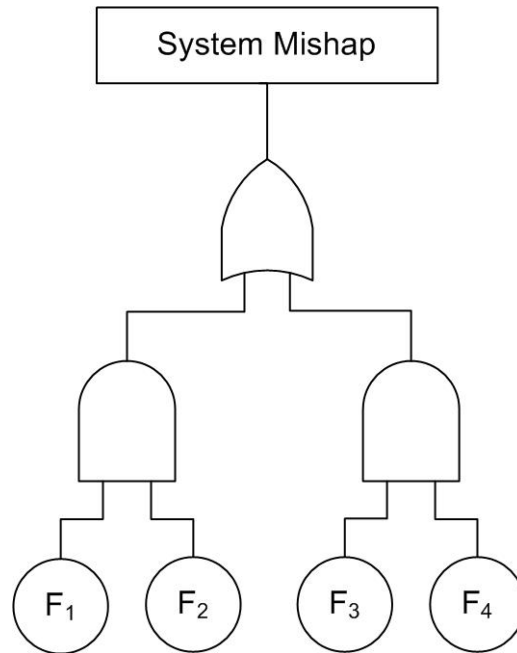


Figure 3. Fault Tree Analysis Example

b. Event Tree Analysis

Event tree analysis is a bottom-up hazard analysis technique that seeks to determine the consequences of a given subsystem or unit failure. It can be visualized as the reverse of a Fault Tree Analysis. The process that is shown in Figure 2 can also be applied to an Event Tree Analysis. However, rather than starting with a top event, Event Tree Analysis starts with a component failure or partial performance. Figure 4 shows an example Event Tree Analysis. The purpose of this tree is to determine the outcome of a 'Component 1 Failure.' Other events in the tree are the components that either depend upon Component 1, or are able to catch the Component 1 Failure and prevent a more serious mishap.

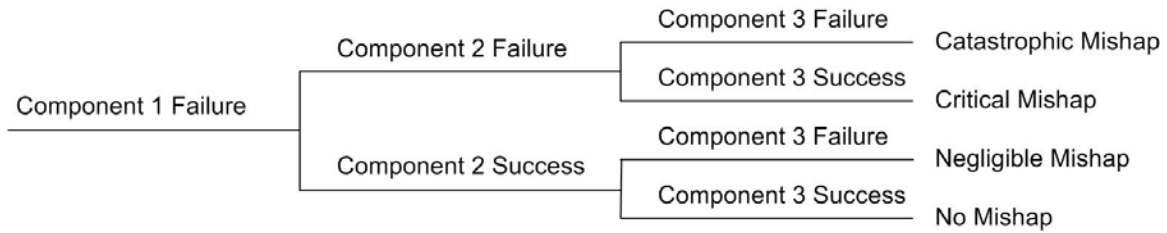


Figure 4. Event Tree Analysis Example

Event Tree Analysis should only be used for specific purposes, when the outcome of a component’s failure is essential to know, or if the probability of failure of a particular component is high. Event Tree Analysis should not be used to cover the entire system, as it has some significant flaws. Firstly, it cannot deal with unrelated initiating failures that may compound further along the failure chain. Secondly, a significant amount of effort can be expended on Event Tree Analyses that provide no fruitful results. A long and complicated Event Tree Analysis may actually result in no hazards being identified. Event Tree Analyses should be used to supplement other hazard analysis techniques.²⁸

c. Hazards and Operability Analysis

Hazards and Operability (HAZOP) Analysis applies a systematic exploration of system parameters and the manner in which they can fail. For each system parameter, a list of guide words is applied in order to determine how the system may fail and what the effects of that failure are. The HAZOP process is summarized in Table 2, but the backbone of the process is:

$$\text{Guide Word} + \text{Parameter} = \text{Deviation}^{29}$$

For example, when dealing with a coolant system, the parameter may be “Flow” and the guide word could be “None,” which results in the deviation, “No Flow”. Other guide words could be more, reverse, less, etc.

²⁸ C. Ericson (2005). *Hazard Analysis Techniques for System Safety* Hoboken, NJ: Wiley-Interscience, p. 233.

²⁹ Ibid., p. 369.

Step	Task	Description
1	Define System	Define, scope and bound the system. Define the mission, mission phases and mission environments. Understand the system design and operation. Note that all steps are applicable for a software HAZOP.
2	Plan HAZOP	Establish HAZOP analysis goals, definitions, worksheets, schedule and process. Divide the system under analysis into the smallest segments desired for the analysis. Identify items to be analyzed and establish indenture levels for items/functions to be analyzed.
3	Select Team	Select team leader and all team members to participate in HAZOP analysis and establish responsibilities. Utilize team member expertise from several different disciplines (e.g. design, test, manufacturing, etc.).
4	Acquire Data	Acquire all of the necessary design and process data needed (e.g., functional diagrams, code, schematics and drawings) for the system, subsystems and functions. Refine the system information and design representation for HAZOP analysis.
5	Conduct HAZOP	<ol style="list-style-type: none"> a. Identify and list the items to be evaluated. b. Establish and define the appropriate parameter list. c. Establish and define the appropriate guideword list. d. Establish the HAZOP analysis worksheet. e. Conduct the HAZOP analysis meetings. f. Record the HAZOP analysis results on the HAZOP worksheets. g. Have the HAZOP analysis worksheets validated by a system engineer for correctness.
6	Recommend Corrective Action	Recommend corrective action for hazards with unacceptable risk. Assign responsibility and schedule for implementing corrective action.
7	Monitor Corrective Action	Review the HAZOP at scheduled intervals to ensure that corrective action is being implemented.
8	Track Hazards	Transfer identified hazards into the hazard tracking system.
9	Document Hazop	Document the entire HAZOP process on the worksheets. Update for new information and closure of assigned corrective actions.

Table 2. HAZOP Process³⁰

³⁰ From C. Ericson (2005). *Hazard Analysis Techniques for System Safety* Hoboken, NJ: Wiley-Interscience, p. 369.

The choice of guide words is dependent upon the system to be analyzed. For most applications, there are lists of guide words that have historically proven to be effective in identifying hazards. An example list of guide words for software and system interfaces is shown in Table 3.

Guide Word	Meaning
None	Intended result not achieved
More	Too much of some parameter
Less	Not enough of a parameter
As Well As	Unintended activity or material
Part Of	Parts of the parameter are missing
Reverse	Value is opposite of intended value
Other Than	Something other than intended result happens
Omission	Intended output missing
Commission	Unintended output
Early	Output occurs too soon
Late	Output occurs too late
Coarse Incorrect	Output's value is wrong
Subtle Incorrect	Output's value is wrong, but cannot be detected

Table 3. HAZOP Guide Words for Software or System Interface Analysis³¹

The HAZOP process provides a systematic approach to identifying system hazards by ensuring that all system parameters and all failure modes are addressed, as well as providing structure to brainstorming sessions. However, it

³¹ J. Reese, and N. Leveson (1997). *Software Deviation Analysis Proceedings of the 19th International Conference on Software Engineering* pp. 250-260.

does have some limitations, namely that it does not consider multiple event failures, it can take considerable effort and time to complete, and a poor choice of guide words can result in some hazards being overlooked.³²

G. SYSTEMS OF SYSTEMS HAZARD ANALYSIS AND THE SYSTEM SAFETY PROCESS

1. Overview

A system of systems hazard analysis should be conducted within the system safety program in order to maximize compatibility with system hazard analyses and to minimize the impact on the training, experience and knowledge base of the system safety engineering community. Some or all of the activities within the system safety process may not be capable of handling the size and complexity of a system of systems. Each of the system safety process steps will be assessed to determine whether a new process will be required for that step to accommodate systems of systems.

2. Documentation of the System Safety Approach

The documentation of the system safety approach for a system of systems can be developed in the same manner as the documentation for a system. Although the actual approach to be documented will differ, the list of elements to be documented remains the same; that is, the documentation must still cover the hazard analysis and mishap risk assessment processes, as well as the means for communicating risk, and so on. Documentation of the system safety approach does not require a new process in order to be applied to systems of systems.

3. Identification of Hazards

Systems of systems hazards cannot be economically and systematically identified by any established hazard identification process. This is due to the size and complexity of systems of systems. Hazard identification processes, such as HAZOP, require engineers to analyze each aspect of the system by hand to determine what hazards may exist. While this could be done for a system of systems, it is not practical as it would take a very long time. Not only are systems

³² C. Ericson (2005). *Hazard Analysis Techniques for System Safety* Hoboken, NJ: Wiley-Interscience, pp. 376 – 379.

of systems exponentially larger and more complex than systems, they also have a large number of configurations, each of which must be analyzed individually. Identification of hazards requires a new process in order to be applied to systems of systems.

In addition, it is difficult to determine the emergent behaviors of a system of systems before the systems are integrated. As such, the hazards that are associated with the emergent behaviors cannot be determined until the system is integrated.

4. Assessment of Mishap Risk

The assessment of mishap risk is dependent upon how the hazards are identified. Given that systems of systems will require a new process in order to identify hazards, it is therefore also true that systems of systems will require a new process to assess the mishap risk. However, the basic structure of the assessment should not change. That is, each hazard should be assigned a qualitative probability and consequence in a manner consistent with a systems assessment. This will allow direct comparisons between hazards identified by any new process and hazards identified by an established process. Assessment of mishap risk will require a new process in order to be applied to systems of systems.

5. Identification of Mishap Risk Mitigation Measures

The measures that may be used to mitigate system of systems hazard risk are similar to those used to mitigate system hazard risk. There may, however, be more aspects of the hazard to attack given the increased complexity of systems of systems hazards. Identification of mishap risk mitigation measures does not require any new processes or measures in order to be applied to systems of systems.

6. Reduction of Mishap Risk to an Acceptable Level

The mishap risk reduction measures can be implemented for systems of systems in the same manner as for systems. The effort required to mitigate a complex system of systems hazard may be more than that required to mitigate a

system hazard, but the methods to be applied are the same. That is, safety requirements can still be added to system specifications, the design can still be changed to reduce the hazard probability and training procedures can still be implemented. Reduction of mishap risk to an acceptable level does not require any new processes in order to be applied to systems of systems.

7. Verification of Mishap Risk Reduction

Verification of mishap risk reduction techniques are the same for systems of systems as they are for systems. Analysis, inspection and test are all valid methods for verifying system of systems hazard risk reduction. Verification of mishap risk reduction does not require any new processes in order to be applied to systems of systems.

8. Review of Hazards and Acceptance of Residual Mishap Risk

An appropriate authority must accept the residual mishap risk for a system of systems. However, the size and complexity of a system of systems means that, unlike a system, a hazard analysis is unlikely to be complete. It is thus difficult to know what the residual risk is. For a system, the residual risk is clearly defined by the identified hazards and the knowledge that the hazard assessment is complete. For a system of systems, an estimate of the residual risk must be made with the knowledge that the hazard assessment is likely to be incomplete. Review of hazards and acceptance of residual mishap risk will require a new process in order to be applied to systems of systems.

9. Tracking of Hazards and Residual Mishap Risk

Tracking of hazards and residual mishap risk is significantly more difficult for systems of systems than it is for systems. Modifications to a system within a system of systems may have far reaching and unknown effects on the hazard space of the system of systems, far beyond the extent of the localized modification. In order for the hazards of a system of systems to be tracked efficiently throughout the lifecycle, a new process is required.

10. Conclusion

The hazard assessment of systems of systems should fit within the system safety process. In order for this to occur, several new processes are

required to complete some of the steps within the system safety process; other steps can be completed without any new processes. In order to complete the system safety process for a system of systems, new processes are required for:

- (i) Identification of hazards,
- (ii) Assessment of mishap risk,
- (iii) Review of hazards and acceptance of residual mishap risk, and
- (iv) Tracking of hazards and residual mishap risk.

H. THE PROBLEM

A system of systems is typically a hazardous and extremely complex entity that must be engineered to meet acceptable safety standards. The size and complexity of a system of systems is such that system hazard analysis techniques are not effective.³³ New hazard analysis techniques must be developed that are able to deal with the size and complexity of a system of systems, that can keep pace with the evolution of a system of systems over the life cycle and that can either cover the full scope of a system of systems or conducts the analysis in such a way that it is clear what aspects of the system of systems have not been assessed and what the residual mishap risk is.

I. CONCLUSION

Systems of systems are complex and hazardous entities. The complexity of a system of systems is sufficient to render system hazard analysis techniques incapable of providing full coverage, and thus applying these techniques may leave some hazards undetected. A new hazard analysis technique is required.

The new hazard analysis technique must fit within the system safety program framework. For some steps of the system safety process, there are established techniques available that can be applied to systems of systems. The following steps need new techniques to be developed:

³³ B. Michael, A. Nerode, and D. Wijesekera (2006). On the Provision of Safety Assurance via Safety Kernels for Modern Weapon Systems *Proceedings of the Fifth Workshop on Software Assessment* p. 103.

- (i) Identification of hazards,
- (ii) Assessment of mishap risk,
- (iii) Review of hazards and acceptance of residual mishap risk, and
- (iv) Tracking of hazards and residual mishap risk.

In the following chapters, a hazard analysis technique will be developed that can identify certain types of systems of systems hazards. This technique will then be applied to the Ballistic Missile Defense System in order to validate the effectiveness of the technique.

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III. SYSTEMS OF SYSTEMS HAZARDS

A. INTRODUCTION

In order to effectively identify, analyze and mitigate systems of systems hazards, the type and nature of these hazards must first be defined. This chapter will describe the nature of the systems of systems hazard space and then break systems of systems hazards down into subtypes that can be directly addressed with identification and analysis techniques.

B. SYSTEMS OF SYSTEMS HAZARD SPACE

A system of systems introduces new hazards that are not present in the individual systems. These hazards are varied and complex, significantly more so than the individual system hazards. In order to determine what hazards *are* present in a system of systems, it must first be determined what type of hazards *may* be present.

Organization of a set of systems into a system of systems creates emergent behavior, but does not change the physical nature of the component systems. For a mishap to occur a system must control or create energy and that energy must be released in an unsafe manner. Integrating a set of systems does not introduce any new energy sources. As such, no new potential mishaps are introduced. More specifically:

$$\{\text{System of Systems Mishaps}\} = \text{Union of}\ \{\text{System Mishaps}\}$$

Note that while the potential mishaps do not change, the probability that a mishap will occur may be changed dramatically. A mishap that is bordering on impossible within a single system may be significantly more probable when combined into a system of systems. In addition, the emergent behaviors of the system of systems create new means by which the mishaps can occur, that is, they create new hazards.

$$\{\text{System of Systems Hazards}\} \neq \text{Union of}\ \{\text{System Hazards}\}$$

These relationships are not new; they are an extension of the relationships between a system and its integrated components. A system of systems is similar to a system in that they both entail the integration of less complex components or systems into a more complex system or system of systems that exhibits emergent behaviors that the components or systems cannot perform on their own.

As an example, consider the simplest of interactions between a forward observer (such as an AWAC aircraft) that is providing target data to a destroyer armed with Tomahawk surface to surface missiles. The destroyer has the potential to launch a Tomahawk against the wrong target which, if the location turns out to be civilian or friendly, results in a mishap. This mishap can occur whether or not the destroyer is part of the larger system of systems. However, if the destroyer is not part of the larger system of systems, a launch against an incorrect target must be caused within the destroyer system. Once the destroyer becomes part of the system of systems, there are new ways that the erroneous launch can occur. That is, the forward observer can provide incorrect target information to the destroyer. The creation of the system of systems (albeit simple) has not introduced a new mishap, but it has introduced a new hazard.

The theoretical hazard space of a system of systems is shown diagrammatically in Figure 5. Each system that is part of a system of systems brings with it its own hazards. That is, the hazard space of System of Systems 1 is at least equal to the hazard space of individual systems A, B and C. Each of the hazards present in these systems may still occur within a system of systems context and are hence part of the set of system of systems hazards. However, there are also hazards within the system of systems that cannot be allocated to a single system. These are emergent hazards. In the above example, when a forward observer provides incorrect target data to a destroyer, and the destroyer launches a Tomahawk at the incorrect target, the resultant hazard cannot be solely attributed to either the forward observer or the destroyer. It is a hazard that belongs to the system of systems.

Figure 5 also demonstrates that system of systems hazards are context dependent. One of the advantages of a system of systems is that it is reconfigurable, both dynamically and through system replacement, removal or addition. This allows the system of systems to adapt to changing functional requirements or operational scenarios. For example, consider if System of Systems 1 is reconfigured such that System A is replaced by System E and System F is added. The hazard space is now altered to System of Systems 2. While the core of the System of Systems (Systems B and C) remains the same, and the function may remain ostensibly the same, the hazard space has been altered dramatically. In addition to the new hazards introduced by the new configuration, there may also be hazards introduced by the transition between configurations.

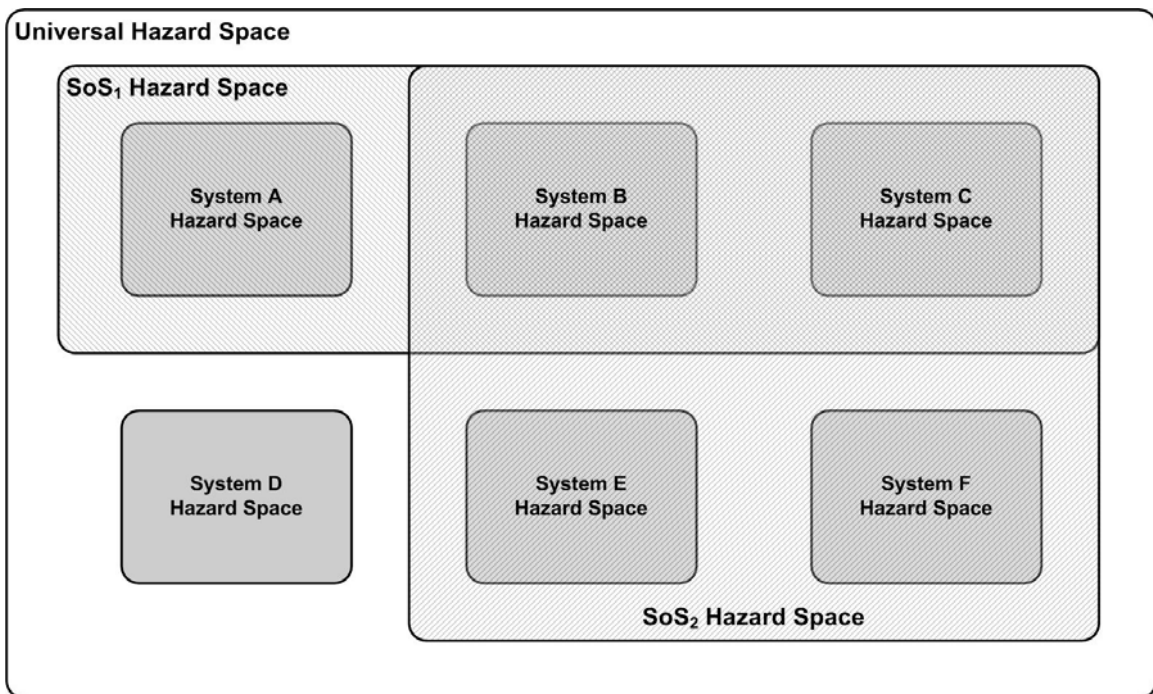


Figure 5. Systems of Systems Hazard Space

C. TYPES OF SYSTEMS OF SYSTEMS HAZARDS

1. Overview

Given that a system of systems introduces new hazards that are not present in the component systems, it must be determined what types of hazards are introduced. It is evidently possible for a system of systems hazard to be extremely complex. The more that is known about the types of hazards that may exist, the more likely it is that the hazards that do exist will be found.

Systems of systems hazards are easily separable into two distinct categories, single system hazards and emergent hazards. A single system hazard is a hazard that is attributable to a single system alone, an emergent hazard is a hazard that results from the integration of several systems into a system of systems and hence cannot be attributed to a single system. Emergent hazards can be further subdivided into reconfiguration hazards, integration hazards and interoperability hazards. The taxonomy of systems of systems hazards is shown in Figure 6. These hazard types are further defined below.

Definition: A *system of systems hazard* is any hazard that may occur within a system of systems.

Definition: An *emergent hazard* is any hazard that may occur within a system of systems that is not attributable to a single system.

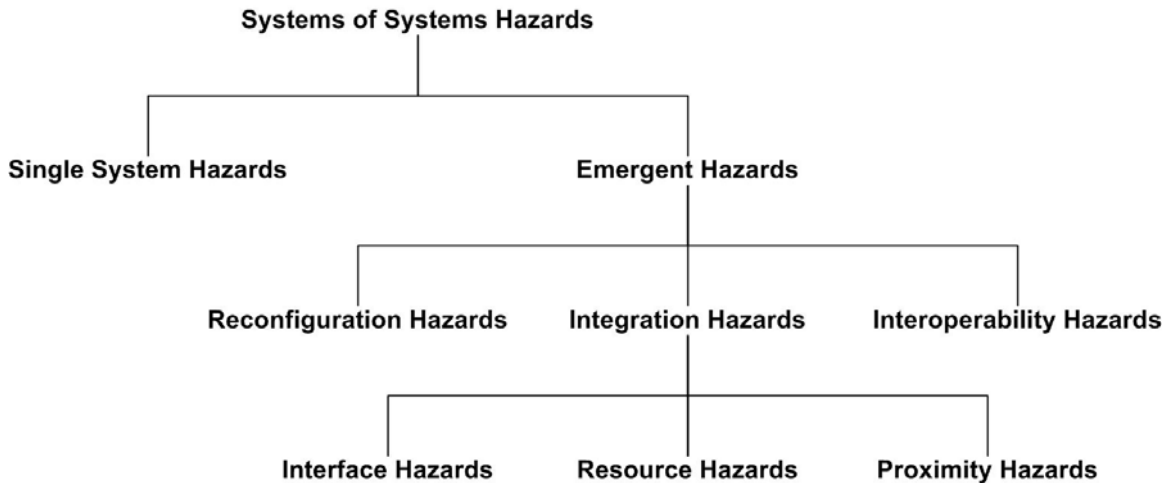


Figure 6. Systems of Systems Hazard Taxonomy

2. Single System Hazards

A single system hazard is a hazard that is attributable to a single system alone. These hazards are identified by the system hazard analysis process and are outside the scope of a system of systems hazard analysis. The purpose of a system of systems hazard analysis is to identify all systems of systems hazard except for single system hazards.

Definition: A *single system hazard* is any hazard that may occur within a system of systems that is attributable to a single system and may occur whether or not that system is operating within the system of systems context.

3. Integration Hazards

a. Overview

Integration hazards are a type of emergent hazard that result from the integration of systems into a system of systems. The vast majority of systems of systems hazards are integration hazards, which can be further subcategorized into three types, interface hazards, proximity hazards and resource hazards.

b. Interface Hazards

Definition: An *interface hazard* is a hazard in which one system causes a mishap in another system by transferring a failure or partial performance over a defined interface, possibly through another system.

The dependency between systems within a system of systems can result in a failure in one system causing a mishap in another. What may be a benign failure in one system may be catastrophic when transferred to another. Figure 7 shows several ways in which a failure in one or more systems can have an adverse effect on another. In the top example, a failure in System A is transferred to System B, which suffers a mishap. In the middle example, a failure occurs in System C that causes a dependent failure in System D, which then causes a mishap in System E. In the lower example, failures occur in both Systems F and H and combine to form a mishap in System G. Within a system of systems, there are enumerable ways in which system failures can combine to cause mishaps. Fortunately, the types of failures which can be transferred are limited by the interfaces between systems.

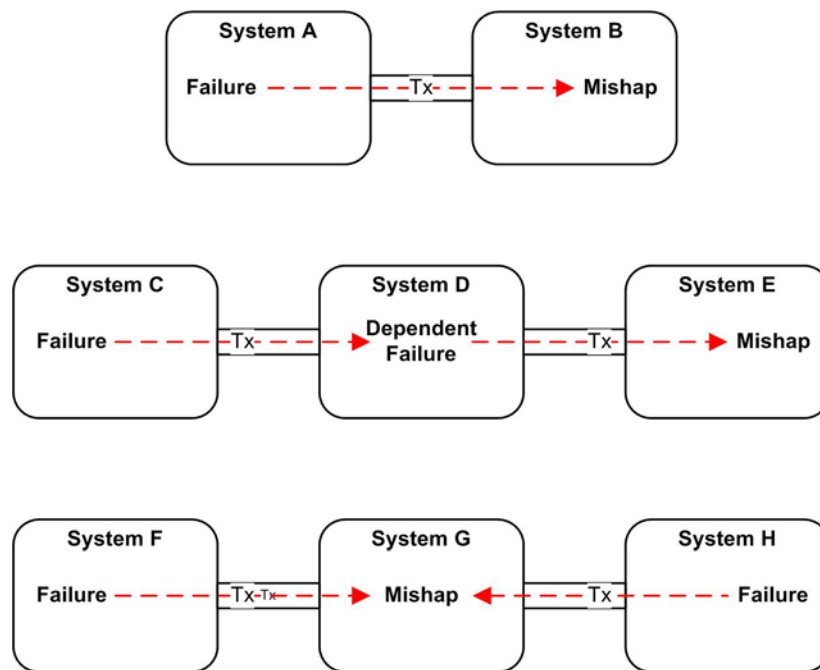


Figure 7. Interface Hazard Examples

A real life example of an interface hazard within a system of systems was the unfortunate shooting down of two U.S. Army Blackhawk

helicopters over Iraq by two U.S. Air Force F-15s. The Blackhawk helicopters were present in the No-Fly zone when the F-15s commenced their patrol. The F-15s were unable to positively identify the helicopters, which appeared as an unidentified contact on their radar screens. There was an Airborne Warning and Control (AWAC) aircraft in the region that also had contact with the helicopters. Although the AWAC aircraft correctly identified the helicopters as friendly, when the information was passed to the F-15s the helicopters were designated as unidentified. Based on this information, the F-15s destroyed the Blackhawk helicopters.³⁴

The Blackhawk friendly fire incident is an example of an interface hazard. Although there were other contributing causes (not discussed), a significant contributing factor was the dependence of the F-15 upon the AWAC aircraft. The failure within the AWAC aircraft (misidentifying the radar contact) was transferred to the F-15 via a defined interface (in this instance, radio communications). A diagrammatic representation of this incident as an interface hazard is shown in Figure 8.

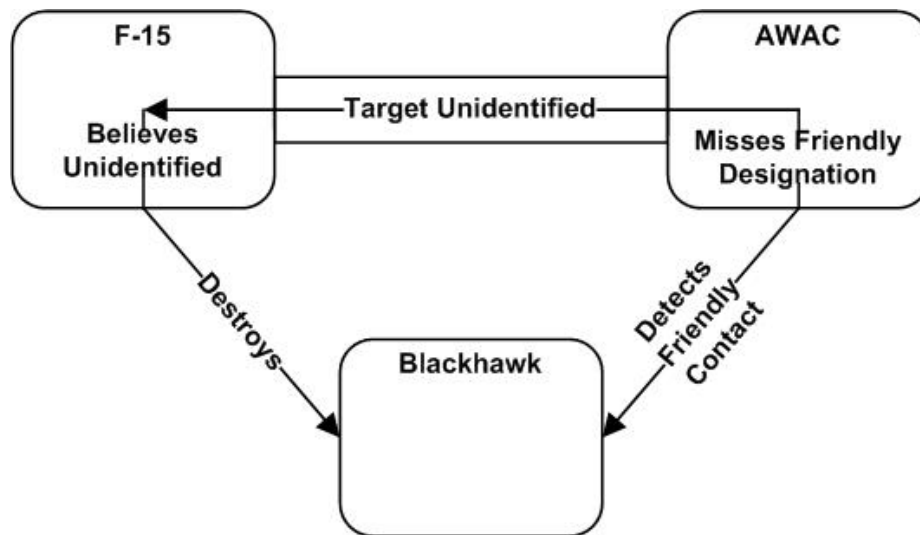


Figure 8. Interface Hazard Model of the Blackhawk Friendly Fire Incident

³⁴ R. Alexander, M. Hall-May, and T. Kelly (2004). Characterisation of Systems of Systems Failures. *Proceedings of the 22nd Annual System Safety Conference*. Unionville, VA, System Safety Society.

c. **Proximity Hazards**

Definition: A *proximity hazard* is a hazard in one system that is caused by the operation, failure or partial performance of another system that is transferred to the victim system by a means other than a defined interface.

A system of systems utilizes a network of systems that is, more often than not, geographically distributed. However, the systems of a system of systems operate with a certain amount of autonomy. As such, it is possible that systems may come within close physical proximity of one another. In some systems of systems, systems may come in close proximity as a part of regular operations. An interface hazard occurs when one system adversely affects another system via a defined interface. When systems come within close³⁵ proximity of each other, it is possible for one system to adversely affect another system without using a defined interface. This is a proximity hazard.

Figure 9 demonstrates the concept of a proximity hazard. System B radiates some form of energy. This radiation may be the result of a failure, but may also be the result of normal operation. Systems A₁ and A₂ are identical systems. System A₁ suffers a mishap as it is close enough to System B to suffer adverse effects. System A₂ does not suffer a mishap as it is sufficiently removed from System B to avoid the propagated energy. The types of propagated energy that may cause mishaps in other systems are many and varied, but likely suspects are electromagnetic energy, heat or gas from rocket exhausts and kinetic energy from projectile weapons. The effects of electromagnetic energy may be overt, such as damage to another system through sheer magnitude of energy, or subtle, such as the corruption of data signals through increased noise.

³⁵ Note: Close is a relative term that depends upon the nature of the systems involved. "Close" when dealing with the ignition of a rocket engine is significantly shorter than "close" when dealing with HF transmissions.

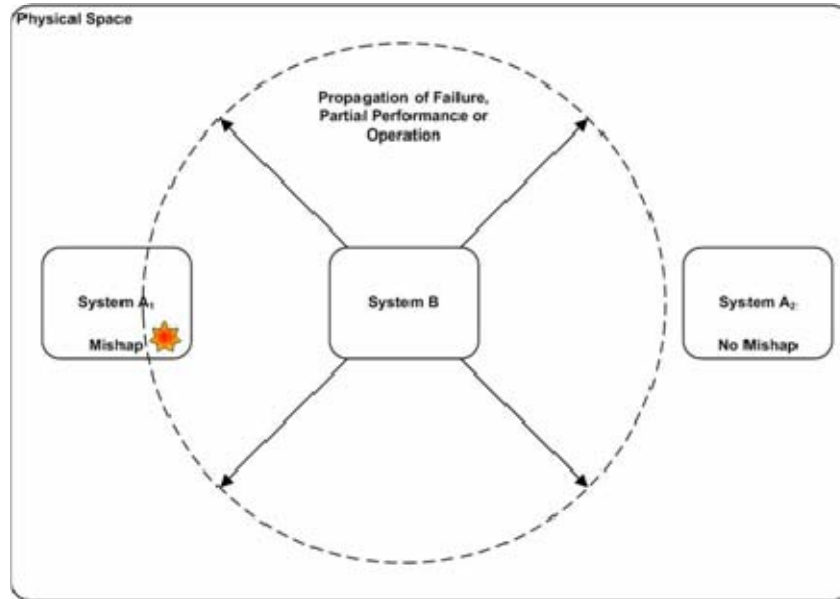


Figure 9. Proximity Hazard Example

A proximity hazard occurred in 1967 off the coast of Vietnam as a U.S. Navy jet was landing on the U.S.S. *Forrestal*. The radar systems on the *Forrestal* caused a short and the uncommanded release of a weapon from the landing aircraft. The weapon struck a fully armed and fueled aircraft sitting on the deck. In the resultant explosion, 134 sailors died and the carrier was severely damaged.³⁶ Aircraft and the weapons they carry are now designed to be less susceptible to electromagnetic radiation. The *Forrestal* accident occurred because the landing aircraft was within close proximity to the carrier and the carrier was propagating energy that had the potential to cause adverse effects in other systems.

d. Resource Hazards

Definition: A *resource hazard* is a hazard that results from insufficient shared resources or resource conflicts.

Systems within a system of systems share resources. When systems, subsystems or components are integrated, unless it is through an

³⁶ National Aeronautics and Space Administration. (1995). *Electronic Systems Failures and Anomalies Attributed to Electromagnetic Interference* (NASA-RP-1374). NASA Marshall Space Flight Center.

outdated point to point wiring, then it is through shared resources. If the systems are dependent upon the resource, or dependent upon the integration that the resource provides, then mishaps may result from a compromise of that resource. Examples of resources that may be shared are bandwidth, airspace, network addresses or memory. There are two types of resource hazards, insufficient resources or resource conflicts. These types of resource hazards are shown in Figure 10. On the left is an example of insufficient resources. Both System A and System B have a requirement for a certain amounts of Resource A. The sum of the systems' resource requirements is greater than the amount of resource available. If either System A or System B is dependent upon access to the resource, then the performance of that system may be degraded or hazardous. On the right is an example of a resource conflict. System C and System D have a requirement for a certain part of Resource B. In this instance, Resource B exists in sufficient amounts to cover the magnitude of the systems' resource requirements. However, System C and System D have requested access to the same section of Resource B. Again, if either system is dependent upon access to Resource B, a hazardous situation may occur.

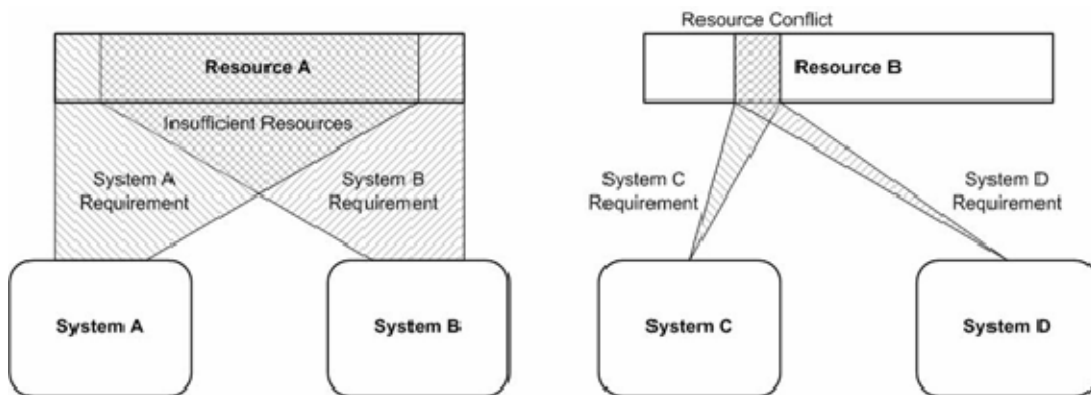


Figure 10. Resource Hazard Examples

Within the system of systems context, the most likely resource hazard to result from insufficient resources is a hazard that results from

insufficient bandwidth. The distributed nature of a system of systems means that communications must travel through the atmosphere, which places a limit on the bandwidth available (as opposed to cable based communications, where bandwidth can be increased by adding cables, atmospheric bandwidth is fixed). An example of this type of hazard may occur when a large number of Unmanned Aerial Vehicles (UAVs) are operating in the same area. If the bandwidth is insufficient to support the number of UAVs, one or more of the UAVs may lose communications and become uncontrollable, resulting in a potentially hazardous situation.

Resource conflicts are particularly applicable to the Air Traffic Control systems of systems that have been envisioned, but not implemented. These systems of systems automatically allocate airspace to inbound aircraft, and some may actually take control of the aircraft. The Air Traffic Control process is effectively the allocation of a limited resource (airspace) to systems (aircraft). A hazardous situation occurs if two or more aircraft are allocated the same airspace. Another example may occur when two previously separate systems of systems networks merge or overlap. The new network is an amalgamation of the previous two, and resource conflicts may occur if two systems have been allocated identical network addresses.

4. Reconfiguration Hazards

Definition: A *reconfiguration hazard* is a hazard that results from the transfer of a system of systems from one state to another.

One aspect of systems of systems which makes them so capable is their ability to dynamically reconfigure as operational needs demand. A system of systems evolves and morphs in both short and long time frames. In the long time frame, new systems are developed and added, old systems are retired. In the short time frame, systems are added or removed from the operating network dynamically depending upon the demands of the task at hand. For example, in times of an elevated threat of ballistic missile launch, the Ballistic Missile Defense System may incorporate more Aegis destroyers and space assets than at normal

threat levels. While this ability brings with it more capability, it also creates a unique type of hazard, the reconfiguration hazard.

Reconfiguration hazards result from changes in state of a system of systems, from one set of systems to a different set of systems, in particular, when the system of systems includes a command and control system. If the command and control system relies upon knowledge of system states, then hazards can result in the transition from one system of systems configuration to another if the state knowledge is lost or unknown for new systems.

Figure 11 graphically demonstrates the concept of reconfiguration hazards. In this example, the system of systems reconfigures from SoS₁, which consists of System A and System B, to SoS₂, which consists of System A and System C. Each system of systems configuration has its own hazard space when in steady state operation. However, the transfer between states introduces new hazards that do not belong to either system of systems hazard space. These reconfiguration hazards belong to the transition process and exist only during and slightly after the transition.

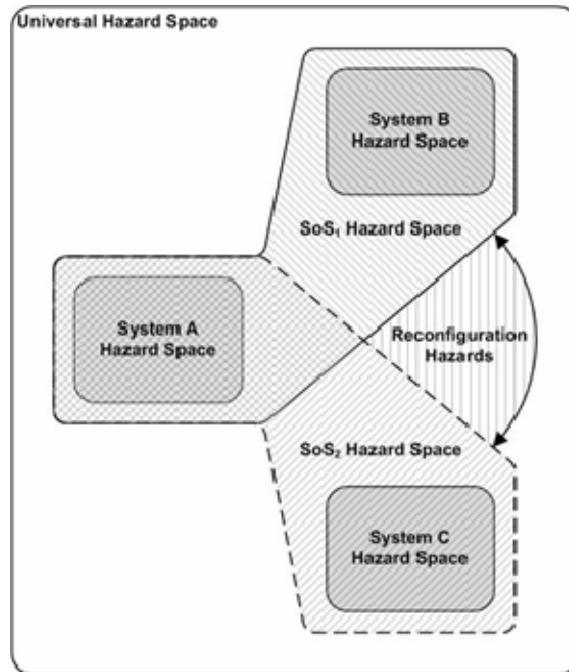


Figure 11. Reconfiguration Hazard Example

Reconfiguration hazards may be the most complicated of the systems of systems hazards, though tangible examples do exist. Prime candidates for reconfiguration hazards are systems that have several states, some of which are hazardous and some of which are not. Within the Ballistic Missile Defense System, there are several systems that have safe and hazardous states. A possible reconfiguration hazard exists between the Command and Control centers and the Ground-based Midcourse Interceptors. The Ground-based Midcourse Interceptors have the ability to kill threat ballistic missiles in the midcourse phase of flight, which means that interceptors based in a confined geographical location have the ability to kill ballistic missiles in orbit that may be targeted at almost any place on earth. As such, it is possible that the interceptors may come under the control of more than one Command and Control center. A hazard may occur when the Command and Control center that currently commands the interceptor places the missile in a maintenance or diagnostic state and subsequently, a second Command and Control center detects a threat

missile and takes control of the interceptor. Without proper knowledge of the state of the missile, the second Command and Control center, which now has control of the missile, may attempt to launch it from an unsafe state. This hazard results from the reconfiguration of the Ballistic Missile Defense System, and is caused by the loss of state knowledge through the transition.

5. Interoperability Hazards

Definition: An *interoperability hazard* is a hazard that occurs when the command, response or data of one system is interpreted by a second system in a manner that is inconsistent with the intent of the first system.

Interoperability mishaps happen with alarming frequency, in particular when armed forces of different nations are operating in a combined environment. The mishaps generally occur when the intent of one party is not clearly communicated to the other. Neither party is solely at fault. The party that gave the command may have done so in accordance with their rules, as may have the party who responds to the command, and yet a mishap still occurs.

Interoperability hazards occur in much the same way. Neither system necessarily fails, but a mishap occurs when the command, data or response of one system is interpreted by a second system in a manner that is inconsistent with the intent of the first system. This is shown in Figure 12. System B_{V1} and System B_{V2} are different versions of the same system. The difference may be due to operation by a different nation, or a system upgrade that has been applied to one system and not the other. System A transmits Message A to both System B_{V1} and B_{V2} expecting the same response. However, differences in System B_{V1} and B_{V2} cause the systems to interpret the message differently, but not because of a system failure. The different interpretation by System B_{V2} results in a mishap.

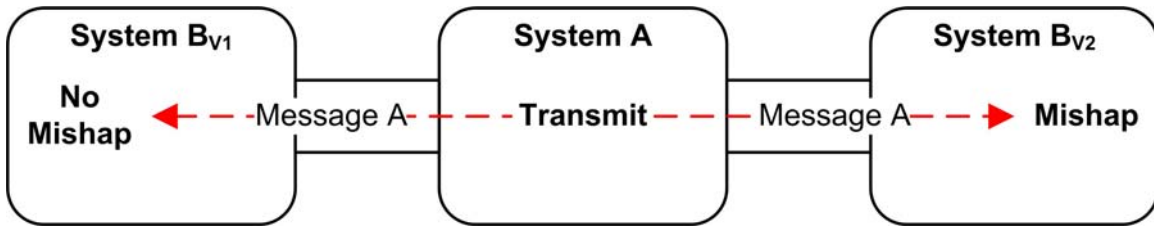


Figure 12. Interoperability Hazard Example

Interoperability hazards can result from incorrect assumptions about how another system operates, for example, an assumption about the coordinate system that is used by another system. Some systems employ a coordinate system with 0 degrees corresponding to true north, others use magnetic north and still others use 0 degrees to represent due east. An incorrect assumption about which coordinate system another system uses may result in a miscommunication of intent, and a potential hazard if the coordinates correspond to an intended target for a missile, or to the airspace assigned to an aircraft under Air Traffic Control.

D. CONCLUSION

There are many types of systems of systems hazards. The purpose behind defining the different types of systems of systems hazards is to gain a greater understanding of these hazards in order to better devise technique for detecting them.

A system of systems hazard is any hazard that may occur within a system of systems. Systems of systems hazards can be broken down into two main types: single system hazards and emergent hazards. A single system hazard is any system of systems hazard that is attributable to a single system. An emergent hazard is any system of systems hazard that cannot be attributed to a single system.

Within emergent hazards, there are three main categories, integration hazards, reconfiguration hazards and interoperability hazards. Reconfiguration hazards result from the transition of a system of systems from one state to

another. Interoperability hazards occur when the interpretation of a message by the receiving system is different from the intent of the transmitting system. Integration hazards further divide into interface hazards, proximity hazards and resource hazards. An interface hazard occurs when a failure in one system is transferred to another system resulting in a mishap. A proximity hazard occurs when one system is able to adversely affect another system outside of a defined interface. Resource hazards occur when there are insufficient shared resources or when there is a resource conflict.

Now that the types and nature of systems of systems hazards have been defined, techniques can be developed to identify and analyze them within real systems of systems. In the next chapter, a technique will be developed that deals with interface hazards. This technique will then be applied to the Ballistic Missile Defense System as a case study to validate the effectiveness of the technique.

IV. INTERFACE HAZARD ANALYSIS

A. INTRODUCTION

Given the complexity of the emergent hazards defined in the previous chapter, it is likely that they will each require a purpose-built assessment technique. In this chapter, a technique will be developed to assess interface hazards within a system of systems. The technique must be cost effective and capable of dealing with significant system of systems evolution. In addition, a technique is described to assess the residual mishap risk from interface hazards.

B. SCOPE

The hazard analysis technique to be developed in this chapter aims to identify and assess interface hazards. It is not intended to identify or assess any other type of system of systems hazards.

Specifically, the technique to be developed in this chapter will achieve the following for interface hazards:

- (i) Identification of hazards,
- (ii) Assessment of mishap risk,
- (iii) Assessment of residual mishap risk, and
- (iv) Tracking of hazards through system of systems evolution.

C. INTERFACE HAZARD ANALYSIS TECHNIQUE OVERVIEW

The interface hazard analysis technique is shown in Figure 13. This technique is designed to complete the system safety program tasks that other techniques are unable to complete for systems of systems, that is, hazard identification and assessment, assessment of residual mishap risk and hazard tracking. The details of the technique are given in Appendix A; what follows is a narrative and description that explains each step.

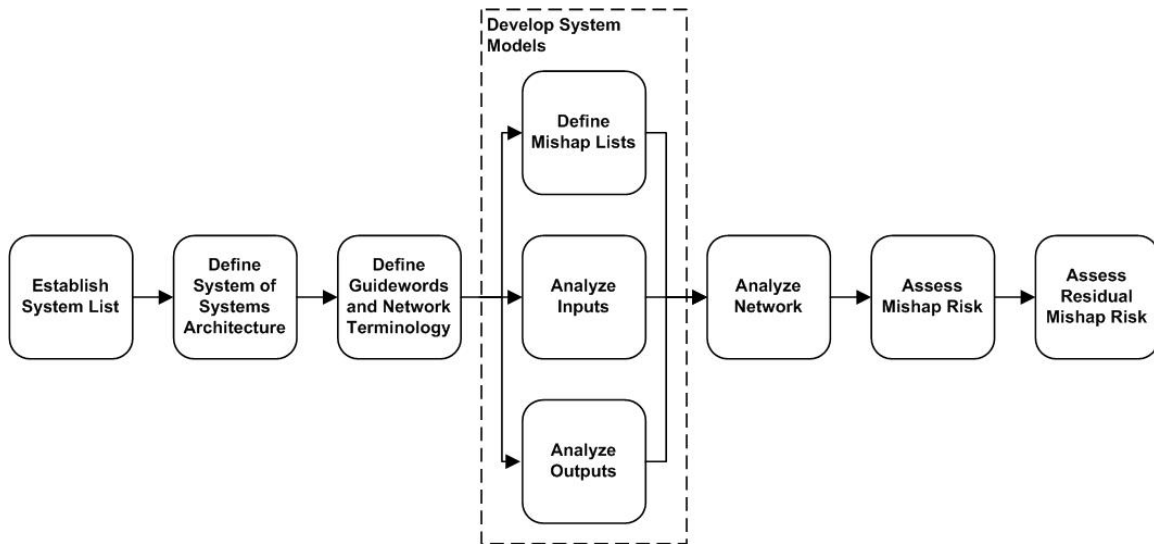


Figure 13. Interface Hazard Analysis Technique Overview

The interface hazard analysis technique steps are as follows, and detailed below:

- (i) **Establish System List.** List all systems that may be part of the system of systems.
- (ii) **Define System of Systems Architecture.** Determine the types of connections each system may have with other systems.
- (iii) **Define Guidewords and Network Terminology.** Define a list of guidewords that will be used to determine system input and output failures and a list of message types, paths and message names.
- (iv) **Develop System Models.** For each system, develop a model that lists all mishaps, output failures and connections between inputs and mishaps or outputs.
- (v) **Analyze Network.** Search the network for connections between systems that can result in mishaps.
- (vi) **Assess Mishap Risk.** For each identified hazard, determine the mishap risk in terms of consequence and probability.
- (vii) **Assess Residual Mishap Risk.** Determine the total risk remaining in the system for all interface hazards.

D. SYSTEMS OF SYSTEMS ARCHITECTURE

Systems of systems exhibit complicated run-time networks. There are a large number of factors that can affect the shape of the network: mission, role, weather, geography and so on. In order to perform an efficient and useful

analysis, the system of systems network must be simplified. The interface hazard analysis technique will deal with possible links between systems, rather than the actual run time links. For the purposes of this analysis, the set of *possible* links defines the system architecture. An example of a system of systems run-time network is shown in Figure 14. This is how the system of systems may look at run time. The systems are geographically distributed and while some systems are able to connect to other systems, geography, weather or operational necessity may prevent them from doing so. In order to perform the analysis, the possible connections must be determined. A hazard analysis deals with events that are possible, though they may not be probable. As such, if it is possible for a connection to occur, it should be included in the architecture.

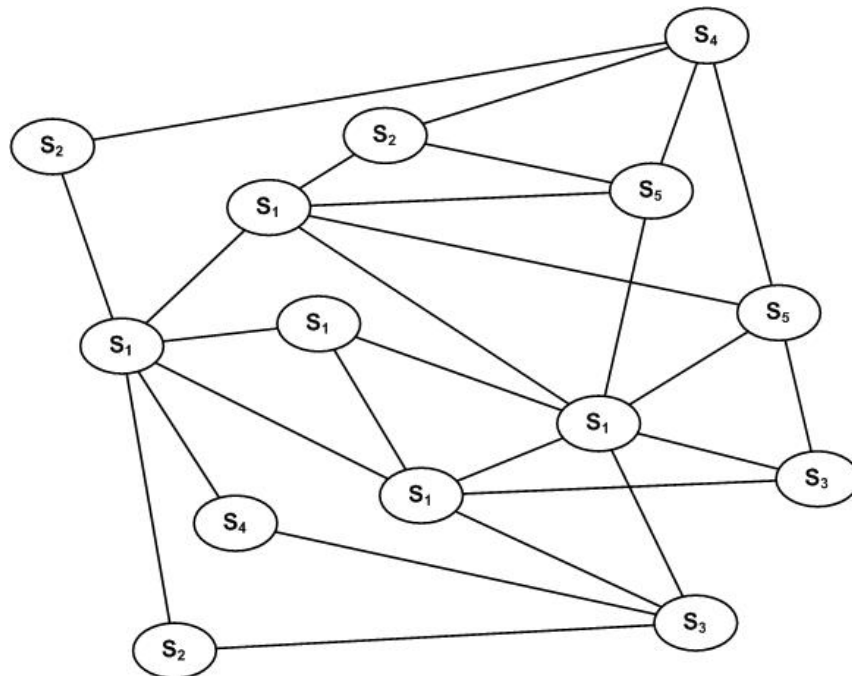


Figure 14. Example System of Systems Network

Figure 15 shows how the system of systems network shown in Figure 14 can be represented as a set of possible connections. There is only one of each system type in the diagram, and rather than deal with which systems actually

connect to each other, it describes how each system may connect to other systems. As such, there is only one link between each pair of systems. In addition, there are only four ways in which a pair of system types can interact:

- (i) 1:1
- (ii) 1:n
- (iii) n:1
- (iv) m:n

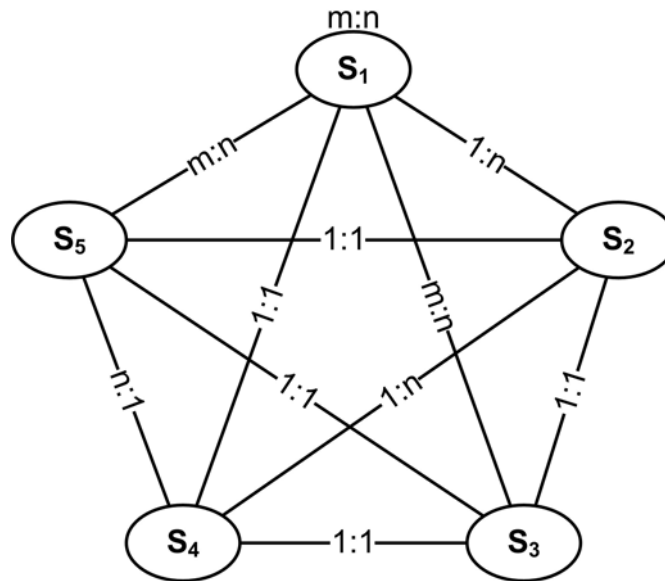


Figure 15: Example System of Systems Architecture Diagram

The diagram shown in Figure 15 may be readable for a system of systems that only includes five system types, but for a larger system of systems, it may become unwieldy, unreadable and unusable. A much simpler, and more usable, representation is shown in Table 4. This table is a summary of the diagram shown in Figure 15. It simply and quickly answers the question “How does System 1 interact with System 2?” This is the pertinent question for interface hazard analyses, which will become more apparent as the technique is further developed.

	S₁	S₂	S₃	S₄	S₅
S₁	m:n	1:n	m:n	1:1	m:n
S₂	n:1	-	1:1	n:1	1:1
S₃	m:n	1:1	-	1:1	1:1
S₄	1:1	1:n	1:1	-	1:n
S₅	m:n	1:1	1:1	n:1	-

Table 4. Example System of Systems Architecture Table

E. SYSTEM MODELS

1. Overview

The system architecture describes how the systems may connect, or communicate, with each other. In order to determine the interface hazards present within a system of systems, the individual system behaviors must be modeled in a manner that is both accurate and cost effective. Systems that operate within a system of systems are complex entities. For a system such as Aegis, an accurate model of the full system may never be developed even for training purposes, let alone for a system safety program. System models are expensive and are unlikely to be fully and accurately developed just for a system safety program. A simple model must be developed that meets the needs of an interface hazard analysis while remaining cost effective.

The simplest system model is the Input/Output (I/O) Model shown in Figure 16. This model describes a system as a 'black box'. That is, it is only concerned with the inputs and outputs of the system, and how they relate. It does not describe how the system transforms the inputs into outputs.

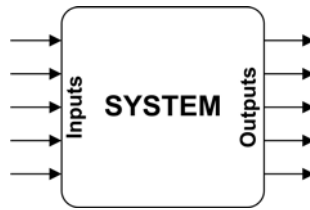


Figure 16. System Input/Output (I/O) Model

The System I/O Model is inadequate for performing an interface hazard analysis. Firstly, an interface hazard analysis requires knowledge of more than just system inputs and outputs. A third concern is mishaps, which may or may not form part of the output set. This third concern modifies the System I/O Model into that shown in Figure 17, the System Input/Output/Mishap (IOM) Model. This model describes a system in terms of the inputs whose failure can cause mishaps or output failures, the outputs that can fail, the mishaps, and the relationships between them.

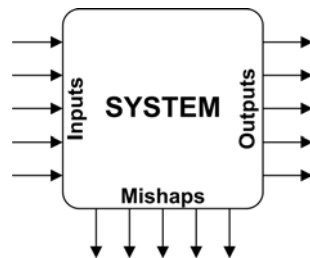


Figure 17. System Input/Output/Mishap (IOM) Model

For the purposes of an interface hazard analysis, a System IOM Model consists of:

- (i) A list of all system mishaps,
- (ii) A list of system input failures and how they link to mishaps or output failures, and
- (iii) A list of system output failures.

The generation of each of these lists is described below.

2. Guide Words and Network Terminology

To ensure that each of the lists that form the system model are consistent and compatible, a standardized set of terms must be used. The system model

deals primarily with possible failures, and hence there must be a consistent list of failure modes for the inputs and outputs of the system. These are the guide words that will be used to identify potential failures. The list of guide words will be application specific, but may be very similar to the guide words used for internal system interface and software Hazard and Operability studies that are shown in Table 3.

In addition, it is necessary to consistently determine the names of the system inputs and outputs. A system input or output consists of a transmission path, a message type and a message name. The transmission path may be a wireless data network, a direct cable connection, a computer network or simple voice communications. The message type will be one of command, data or response. The message name can take on a large number of values. It is important, when comparing inputs with outputs, that consistent terminology be used. For example, an interface hazard may be overlooked if the message name “Target Location” is used for one system and “Location of Target” is used for another.

3. Mishap Identification

Once a consistent terminology has been defined, the first step in creating a system model is to identify the mishaps associated with each system. The mishap list for each system should be simple to determine within a system of systems, or interface hazard analysis, as the mishaps should have been identified as part of the system hazard analysis. The mishap list for a system does not change when it is integrated into a system of systems.

4. Input Analysis

Performing an input analysis is the most significant part of developing a system model. An input analysis is an application of the HAZOP process to the inputs of a system in isolation. It seeks to answer the question: “What is the effect of a given input failure on the mishaps and outputs of a system?”

The analysis starts with a list of system inputs, defined in terms of transmission path, message type and message name, and a list of guide words

that describe how an input may fail. Each guide word is applied to each input in turn, and the effects of that failure on mishaps and outputs assessed. The result is a list of links, from inputs to outputs or inputs to mishaps. It is of no concern at this point whether any other system could actually cause the input failure. Each system must undergo the input analysis process in isolation.

A link can be created between an input and a mishap, as in Figure 18, or multiple inputs and a mishap, as in Figure 19. While there may be many inputs within a link, there should only ever be one mishap. If a set of inputs cause more than one mishap, then a second link, with the same inputs but the alternate mishap, should be created.

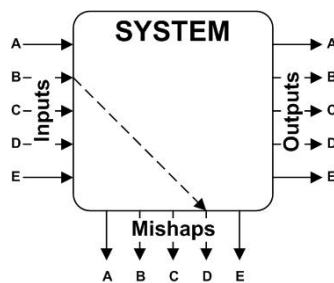


Figure 18. Input to Mishap Link

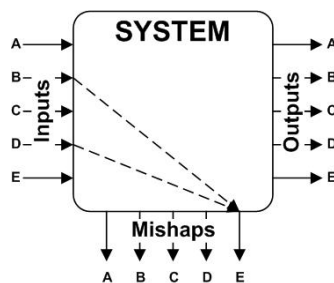


Figure 19. Multiple Inputs to Mishap Link

In addition to causing mishaps, failed inputs can also cause failed outputs. A single failed input may cause a single failed output, as in Figure 20, or it may take more than one failed input to cause a failed output, as in Figure 21. Alternatively, a single failed input may cause numerous failed outputs, as in Figure 22. A link must have a single failed input, or a single failed output, or both.

If the link involves multiple inputs and multiple outputs, then it can be separated into two or more links that meet the single input or single output requirement.

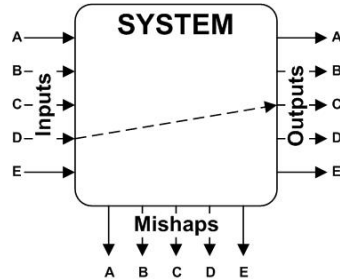


Figure 20. Input to Output Link

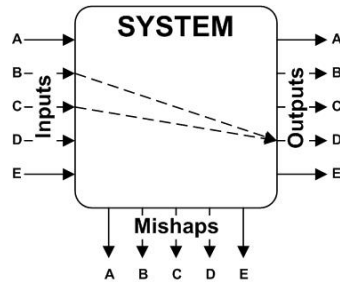


Figure 21. Multiple Inputs to Single Output Link

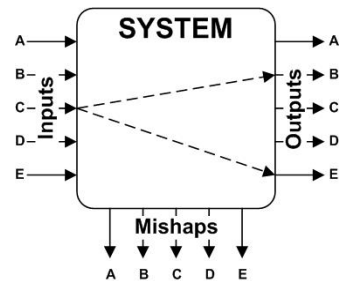


Figure 22. Single Input to Multiple Outputs Link

An input analysis generates a list of dependent events, that is, none of the links that are identified are initiators. They all depend upon other events transpiring. The events that may trigger one of the links from inputs to outputs, or from inputs to mishaps, will be generated in the output analysis.

5. Output Analysis

An output analysis is a HAZOP analysis of the outputs of a system to determine which system outputs can fail as a result of a system failure, and how those outputs fail. It uses the same guidewords as the input analysis, and applies them to each of the system outputs in order to determine whether that type of failure is possible. A list of system failures that can cause the output failure can be used to calculate the probability of the output failing, or in developing mitigation strategies to reduce that probability.

System output failures may occur singly, as in Figure 23, or in groups, as in Figure 24. System outputs should only be grouped if they are inseparable, that is, the set of conditions or system failures which causes one output failure causes every output failure in the group. If it is possible for a subset of the output failures to occur from the conditions and system failures, then a second group of system output failures should be created.

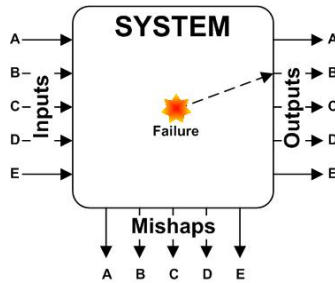


Figure 23. Failure to Output Link

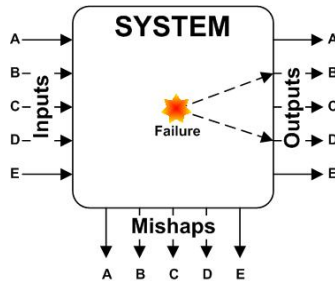


Figure 24. Failure to Multiple Outputs Link

F. NETWORK ANALYSIS

The input analysis and output analysis generates the building blocks for defining interface hazards. It is clear from the description of the links above that a link can be drawn from an initiating failure to a mishap. The purpose of a network analysis is to assemble the links into interface hazards and to ensure that all possible combinations are assessed. Figure 25 shows how the results of an input and output analysis can be assembled to form an interface hazard.

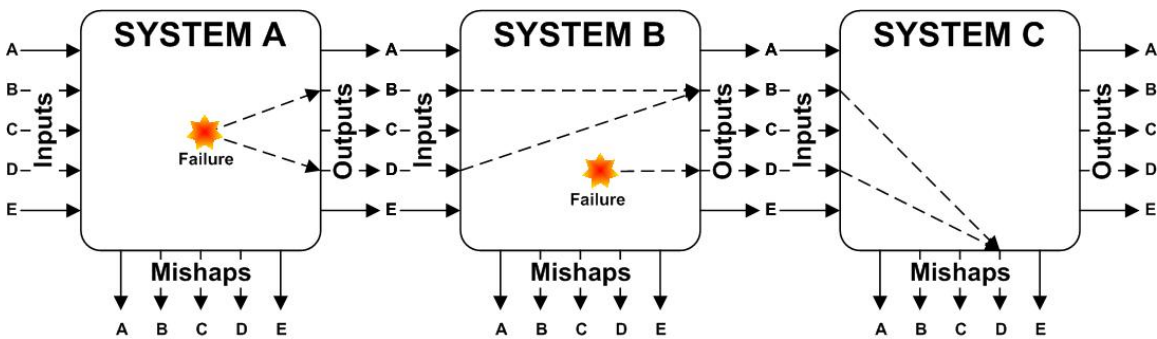


Figure 25. Example Interface Hazard Assembled from System Models

The network analysis technique to be used to identify interface hazards is similar to a Fault Tree Analysis. The analysis starts with an end event, a link from an input to a mishap, and works backwards, adding links from inputs to outputs and failures to outputs. The result is a tree that describes all the ways in which an interface hazard can cause a mishap.

The basic building blocks of a network analysis are shown in Table 5. These symbols are used instead of the IOM Model as there can be a large number of elements in the network analysis and the IOM models are cumbersome.


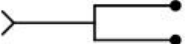

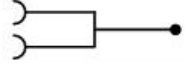
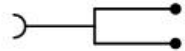

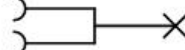
Symbol	Meaning
>	Failure
×	Mishap
)	Input
•	Output
	Failure to Output Link
	Failure to Multiple Outputs Link
	Input to Output Link
	Multiple Inputs to Single Output Link
	Single Input to Multiple Outputs Link
	Input to Mishap Link
	Multiple Inputs to Mishap Link

Table 5. Network Analysis Symbology

An example of how these symbols may be used to define an interface hazard out of the basic elements is shown in Figure 26, which is the symbolic representation of the interface hazard shown in Figure 25. This is a very simple example that shows only one way for the mishap to occur. In reality, there may be many ways for a link to be created between initiating failures and the two inputs that are required to fail for the mishap to occur. Figure 27 is an example of how a network analysis tree is more likely to look. Each dashed box represents the different links which may continue the tree at that point. In this example, there are ten ways that the mishap can occur. Note that the interface hazard described by Figure 25 and Figure 26 is also in Figure 27, shown by the option in red.

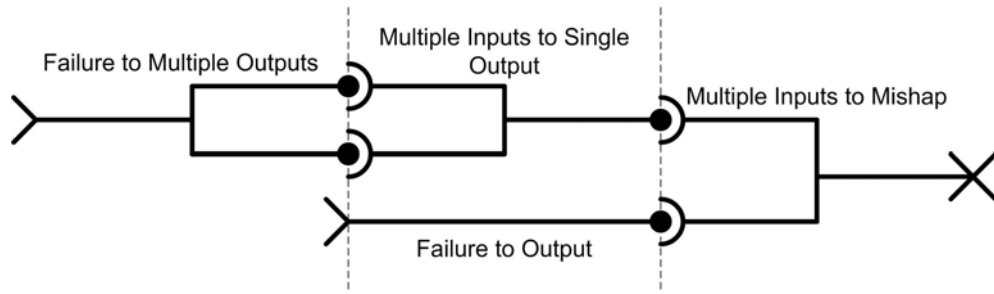


Figure 26. Example Network Analysis

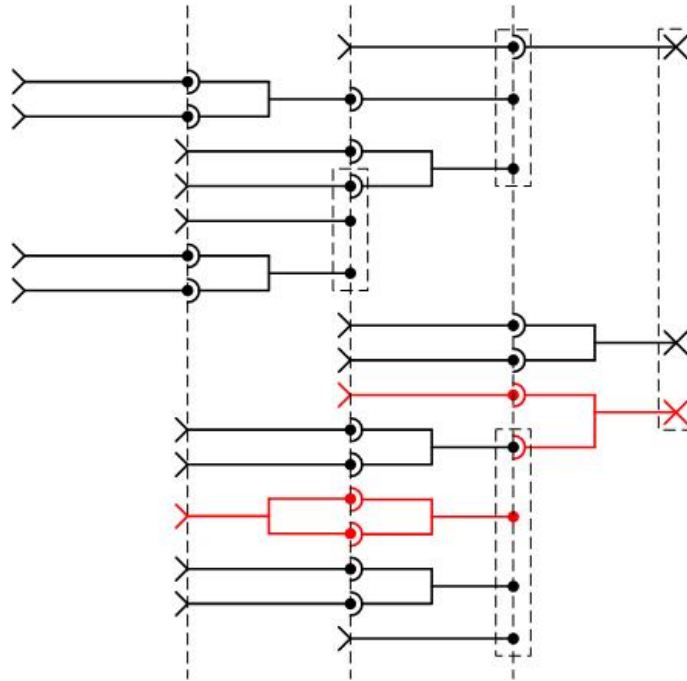


Figure 27. Example Network Analysis Showing Options at Each Stage

There are other ways to identify interface hazards within the network. A brute force method may be used that cycles through every possible combination of systems. However, the top down, tree approach is more efficient and, like the brute force approach, is simple to automate. The ability to automate the network search will become apparent when dealing with very large scale systems of systems that continuously evolve. In this circumstance, it would be inefficient to reproduce the search by hand each time the system of systems changed.

G. ASSESSMENT OF MISHAP RISK

1. Overview

The set of system of systems hazards includes hazards that are identified by the interface hazard analysis technique and hazards that are identified by system hazard analysis techniques. The end result is a list of hazards that must exist in a common database and must be comparable. Hazards that have been identified by a system hazard analysis technique undergo a mishap risk assessment, resulting in a statement of the consequence and probability of the hazard in question. Hazards identified by the interface hazard analysis technique must have a similar assessment.

2. Consequence

The consequence of an interface hazard is the consequence of the mishap at the top of the network analysis tree. Systems of systems mishaps are likely to have been identified during the system hazard analysis process for each individual system and hence the assessment of consequence is also likely to be already complete.

3. Probability

The probability of a interface hazard occurring is a function of the component elements, that is, the links between inputs and outputs, the links between inputs and mishaps, and the links between failures and outputs. Each identified link must be assigned a probability of occurrence. For links between failures and outputs, this probability is the probability that the failure will occur and that that failure will translate to an output failure. For links between inputs and outputs, the probability is the probability that the input failure will be retransmitted as an output failure. For links between inputs and mishaps, the probability is the probability that the mishap will occur given that the input failures have occurred. Each of these probabilities should be assessed qualitatively in accordance with MIL-STD-882D or a similar safety standard.

Once each link in the interface hazard has been identified, and each link has been assigned a qualitatively probability, the probability of the interface

hazard can be determined by combining all probabilities involved. The combination of qualitative probabilities is discussed fully in Appendix B, however the basic principle is to assign a qualitative result to the logical conjunction (i.e., the AND function) of two qualitative probabilities, producing a table like that of Table 6. A two dimensional table is sufficient for all qualitative probability combinations as the AND function is associative.³⁷

AND	Frequent	Probable	Occasional	Remote	Improbable
Frequent	Frequent	Probable	Occasional	Remote	Improbable
Probable	Probable	Occasional	Remote	Remote	Improbable
Occasional	Occasional	Remote	Remote	Improbable	Improbable
Remote	Remote	Remote	Improbable	Improbable	Improbable
Improbable	Improbable	Improbable	Improbable	Improbable	Improbable

Table 6. Example Qualitative Probability Combinations

Consider the example from Figure 26. Suppose the events in Figure 26 are assessed as having the probabilities shown in Table 7. As each event is required for the interface hazard to occur, the hazard probability is (using the qualitative probability combination scheme from Table 6):

$$\begin{aligned}
 \text{Probability} &= \underbrace{\text{Remote AND Frequent}} \text{ AND Occasional AND Frequent} \\
 \text{Probability} &= \underbrace{\text{Remote AND Occasional}} \text{ AND Frequent} \\
 \text{Probability} &= \text{Improbable AND Frequent} \\
 \text{Probability} &= \text{Improbable}
 \end{aligned}$$

As such, the probability of the interface hazard shown in Figure 26 is Improbable.

³⁷ That is, $(a \times b) \times c = a \times (b \times c) = a \times b \times c$, or $(a \wedge b) \wedge c = a \wedge (b \wedge c) = a \wedge b \wedge c$.

Element	Probability
Failure to Multiple Outputs	Remote
Multiple Inputs to Single Output	Frequent
Failure to Output	Occasional
Multiple Inputs to Mishap	Frequent

Table 7. Example Event Probabilities for the Interface Hazard from Figure 26.

H. RESIDUAL MISHAP RISK

The residual mishap risk is a significant system of systems factor. It is the risk that is assumed by the certifying authority and the operators. A system of systems should never be operated without knowing what the residual mishap risk is.

A system hazard analysis may have complete system coverage, and as such, the residual mishap risk can be calculated from the identified risks. A system of systems hazard analysis is unlikely to have complete coverage. A hazard analysis for a system of systems, including the interface hazard analysis technique presented here, is more likely to use a targeted search method that has a high probability of finding the significant hazards. As such, there will be unknowns at the completion of the analysis, resulting in some degree of uncertainty about the actual amount of residual mishap risk.

When dealing with incomplete information, there are three subcategories. You either have the information (known), you are aware that you do not have some information (known unknowns), or you are unaware that you do not have some information (unknown unknowns). In calculating the residual mishap risk for a system of systems, each of these types of information must be taken into account. The information that you have should be analyzed. The information that you do not have, but are aware you do not have, should be assessed as either

acceptable or unacceptable to remain unknown. In the latter case, effort should be made to gain the information. Information that you do not have and do not know that you do not have should be minimized through the use of a high-quality, well-funded exploratory process conducted by the appropriate personnel.

Within an interface hazard assessment, the known information is the list of identified hazards. These hazards can be analyzed to generate an overall risk assessment for the system of systems in terms of interface hazards. However, there are two other factors that affect the residual mishap risk. The first is the interface hazards that are present in the system of systems and are part of the system models but have not been identified by the network analysis. The second is the interface hazards that exist in the system of systems that are not identified because the system models do not accurately represent the systems. The first is a type of known unknown, the second a type of unknown.

Steps can be taken to minimize the impact of interface hazards that are part of the system models but not identified by the network analysis. A network analysis starts with a top-level event, a link from an input to a mishap, and works backwards to determine the events that can cause that mishap. As each new event is added to the tree, the probability that the hazard will occur decreases. As such, at a given level of decomposition, an assessment can be made about all interface hazards that occur beyond that level of decomposition. This assessment will depend upon the qualitative probability combination scheme that is chosen by the analyst.

Consider a qualitative probability combination table that has the result of the combination of two frequent events as less than frequent (e.g., Table 21 or Table 22). The worst-case scenario for an interface hazard with five elements is a direct chain of events, like that shown in Figure 28. The probability of this hazard is improbable. If you add another event to the left of this chain, the probability is still improbable. In fact regardless of how many events you add to the left of this chain, the probability will always be improbable. In addition, if you

add parallel events, say by changing the second order event from a single input single output to a multiple input single output and then add a failure to output in parallel with the third-order event, then the probability is still improbable. If the chain stops at the fourth-order event, then the probability is remote. In this case, addition of extra events, either at the left of the chain or in parallel early in the chain, will decrease the probability.

Thus we can make the following conclusion. For qualitative probability combination schemes where the combination of two frequent probabilities is less than frequent, the network analysis tree need only extend to fifth-order events. If the network analysis tree completely covers all fifth-order or less events, then the probability of all remaining interface hazards is improbable.

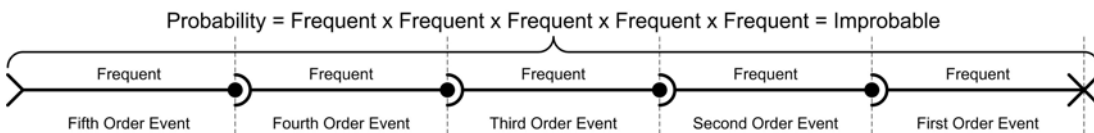


Figure 28. Worst Case Probability Chain for Fifth Order Interface Hazards

If the combination scheme dictates that the combination of two frequent events is still frequent (Table 23 or Table 24), then creating a network tree that decomposes to the fifth level does not guarantee that all other hazards have a probability of improbable. Consider Figure 28, if the combination of Frequent AND Frequent is Frequent, then the probability of the interface hazard in Figure 28 is Frequent. In fact, the chain could extend forever and the probability would still be Frequent. This is a mathematical anomaly within the qualitative probability combination calculations, which allows a frequent event to have a probability of 1, a mathematical possibility but practical improbability. In any event, the chain can only continue to have a frequent probability if there are sufficient frequent events within the system of systems. In this instance, the network analysis tree must be defined four steps past the number of frequent events. For example, if there are only three frequent events within the system of systems, then all

interface hazards that extend past the seventh order will have probabilities of improbable. That is, in the worst-case scenario, the three frequent events will combine to form a chain whose probability is still frequent. Four more events will ensure that this probability is reduced to improbable.

The above assumptions, regarding interface hazards beyond a certain order, refer only to the interface hazards that remain unidentified due to the network analysis. There are other interface hazards that may remain unidentified because of shortfalls in the system models. Regardless of how deep or thorough the network analysis is, these interface hazards will never be identified. These are the unknown unknowns, and they must be minimized. In order to minimize the likelihood of overlooking interface hazards in this manner, the development of the system models must be thorough. This involves a combination of ensuring that the engineers who perform the analyses are experienced and knowledgeable, the list of guide words is appropriate for the application and all aspects of the system inputs and outputs are considered.

In summary, the residual mishap risk of a system of systems due to interface hazards is the culmination of the identified risks, the knowledge that all risks not identified by the network analysis but present in the system models have a maximum probability and the risks that result from unknown system data.

I. SYSTEMS OF SYSTEMS EVOLUTION

Systems of systems evolve over the life cycle. New systems are added, old ones removed and current systems are modified. In order to remain relevant and cost effective, a hazard analysis technique must be able to cope with changes to the system of systems.

The interface hazard analysis technique presented above is able to address system changes. The system models that are developed during the input and output analyses are independent of other systems. That is, an input failure is linked to a mishap regardless of whether there is another system that can cause the input failure to occur. An output failure is defined regardless of

whether there is another system that is susceptible to that failure. In addition, the process that searches for interface hazards, the network analysis, is automated and hence requires little effort to rerun.

Thus the interface hazard analysis technique remains relevant throughout the systems of systems life cycle. In the event of a change to a system or an addition or removal of a system, only the relevant system model need be altered, removed or added. All other system models remain the same.

J. CONCLUSION

The interface hazard analysis technique has been developed to identify and assess interface hazards, assess the residual mishap risk of interface hazards and to track hazards through systems of systems evolution. This technique will fulfill the shortfalls in the system safety program when applied to systems of systems.

The technique has several advantages. Firstly, it does not require complex system models to be developed. A HAZOP analysis of the inputs and outputs of a system will produce a sufficient system model. The system models can then be analyzed within a network to produce the interface hazards. The network analysis is a simple process that can be automated.

Interface hazards are assessed in the same manner as system hazards, that is, they are assessed in terms of probability and consequence. The consequence assessment is the same as for system hazards. The probability assessment involves the combination of the qualitative probabilities of the component events.

The residual mishap risk associated with interface hazards is a function of the identified hazards, the hazards not identified by the network analysis (whose probability is limited) and the hazards not identified due to shortfalls in the system models. The first two can be qualitatively assessed. The last can be minimized through an expert application of the interface hazard analysis technique.

The interface hazard analysis technique can keep track of interface hazards throughout the system life cycle, even in the face of significant systems of systems evolution. The main reason for this is that the system models are independent of each other. They are developed in isolation from the system of systems and do not require alteration when new systems are added. In addition, the network analysis technique is simple to automate, which simplifies repetition of the analysis.

The interface hazard analysis technique is defined in Appendix A. Now that the technique has been described, it will be applied to a case study in the following chapter in order to validate its effectiveness.

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V. APPLICATION OF TECHNIQUE TO CASE STUDY

A. INTRODUCTION

A case study is required to ensure that the interface hazard analysis technique is able to detect interface hazards. The Ballistic Missile Defense System will be used to validate the effectiveness of this technique.

In this chapter, the development of a software application that employs the interface hazard analysis technique will be described. This software application was developed to prove not only the capabilities of the interface hazard analysis technique, but also to prove that a software application that employs the technique was conceptually feasible.

The software application will then be applied to the Ballistic Missile Defense System and interface hazards generated. An overview of the Ballistic Missile Defense System is provided in Appendix C. Representative data will be used to generate system models for the Ballistic Missile Defense System and the case study will be kept sufficiently small to conform to the time constraints of postgraduate research. The intent is that the case study will further confirm the feasibility of the interface hazard analysis technique and the corresponding software.

B. SOFTWARE DEVELOPMENT

1. Overview

In order to validate that the interface hazard analysis technique was practical and capable of producing results, a software application was developed. The application was built as a concept demonstrator. It allows the user to enter system models and then performs a network analysis. While it performs the function of an interface hazard analysis, it is not intended to be used in practice. It does not include the usual level of error checking and user functions that would be expected of an application of this type. It's purpose is to demonstrate that the interface hazard analysis technique described above is feasible.

2. Functional Requirements

The software application was designed in order to meet the following basic requirements:

- (i) the application shall allow the user to enter the system model data,
- (ii) the application shall perform a network analysis on the system model data,
- (iii) the application shall display the interface hazards found during the network analysis to the user, and
- (iv) the application shall allow changes to the system model data to simulate the evolution of a system of systems.

3. Design

The application was developed in Java and employs a GUI to allow the user to enter the system model data and to display the identified interface hazards. The core of the application is the object orientated modeling of a system of systems and the functions that perform the network analysis. The object orientated model of a system of systems is shown in Figure 29.

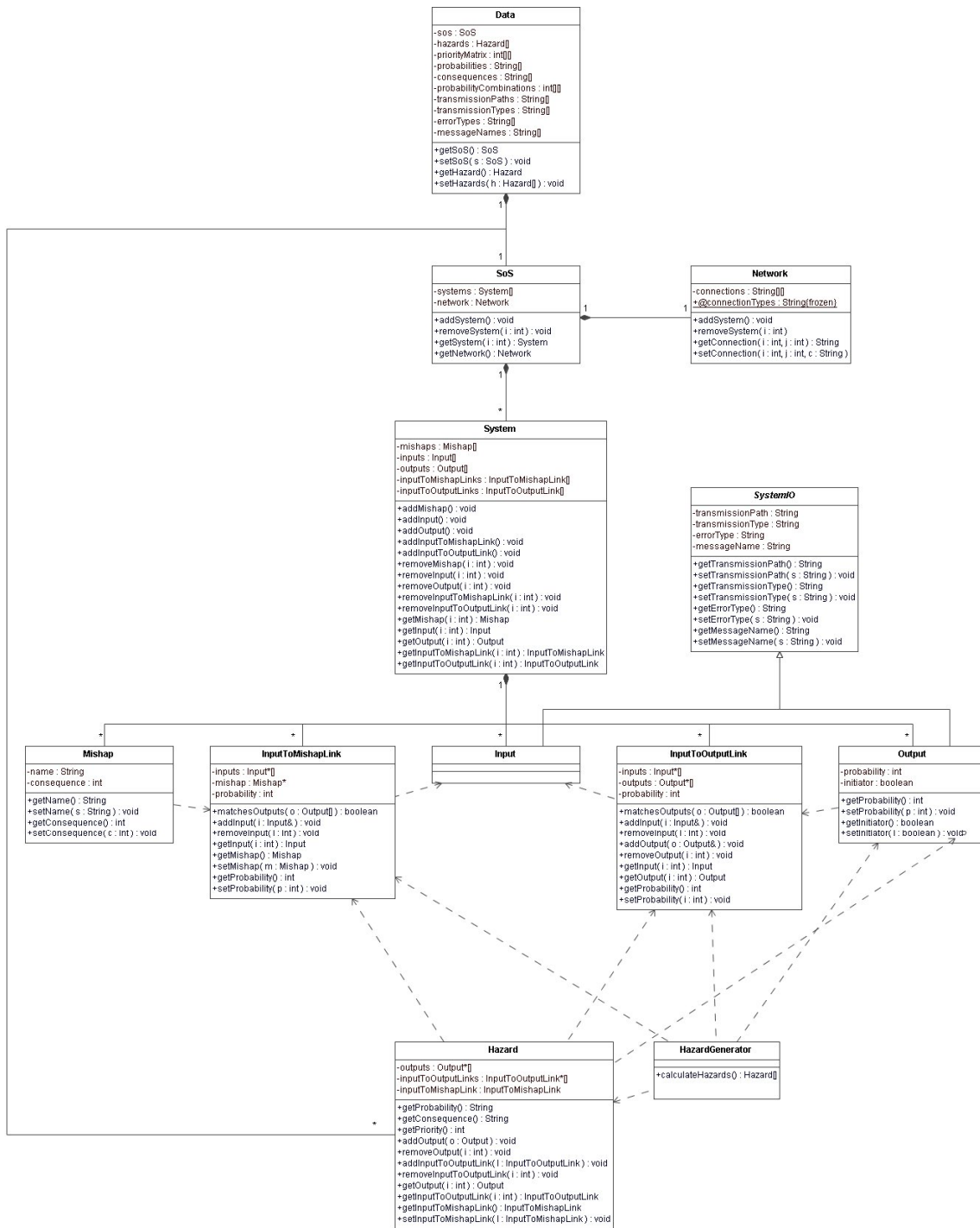


Figure 29. Class Diagram for Interface Hazard Analysis Concept Demonstrator

The model of the system of systems follows the real world structure. The highest level object is a data object that contains a number of application settings and the main system of systems object. Within the system of systems object there is an array of systems and a network object. The purpose of the network object is to track the types of connections that exist between systems. Each system object represents a system that may be present in the system of systems.

The system object is an implementation of the IOM model. It consists of mishaps, inputs, outputs, links from inputs to outputs and links from inputs to mishaps. These are the pieces that will later be constructed into network analysis trees. The inputs, outputs and mishaps are objects that represent the real world nature of the systems. The links are simulations of the real world systems performance. They contain the pointers³⁸ to inputs, outputs and mishaps necessary to describe the links as well as a value that represents the probability that the link will occur. Outputs come in two forms; they may either be used later in a system link or as an initiating event.

A separate hazard generating object is used to perform the network analysis. It creates hazard objects that contain pointers to the links and outputs that describe the hazard. A hazard object is able to calculate the hazard probability, consequence and priority based on its component events. Due to time constraints, the hazard generating object that was used in the concept demonstrator employed a brute force algorithm that searched a number of basic interface hazard schemes. It did not employ a more intelligent and efficient, tree structured search algorithm. Such an algorithm is not a particularly complex task, and its generation was not considered necessary to demonstrate the concept.

³⁸ In Java, this is of little consequence as all object references are pointers. However, this may make a difference if the application is implemented in another language.

The GUI used a relatively simple set of text boxes, drop down boxes and check boxes in order to collect the system model data. The data is stored within its own object and may be written to an XML file for later restoration. An example of the application GUI is shown in Figure 30. This example is typical of the application and is used to collect the input to output links for each system model.

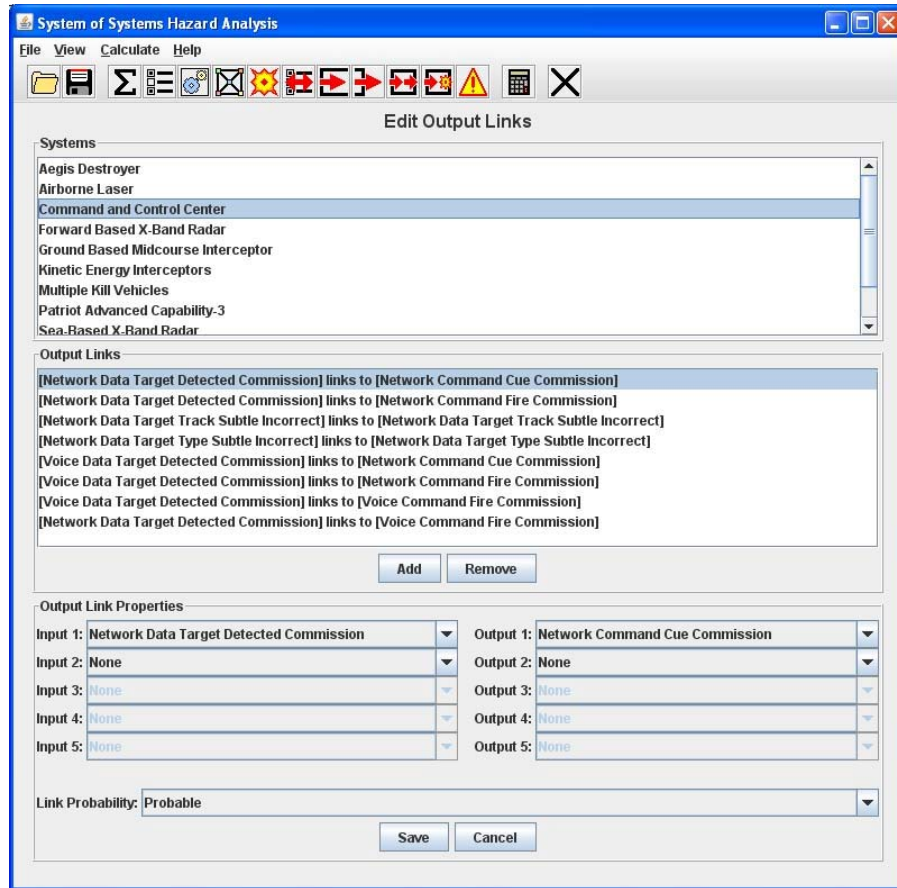


Figure 30. Interface Hazard Analysis Application Screen Shot – GUI

The application also includes interfaces to collect the following data:

- (i) Analysis settings such as the qualitative probability levels, the consequence levels, the calculation of priority from probability and consequence, and the combination of two qualitative probabilities.
- (ii) A complete list of systems within the system of systems.
- (iii) A system architecture table.

- (iv) A list of mishaps for each system.
- (v) System Input/Output settings such as the transmission paths, the message types, the message names and the guide words or error types. All are customizable.
- (vi) A list of inputs for each system.
- (vii) A list of outputs for each system, including those that can initiate an interface hazard.
- (viii) A list of links from inputs to outputs for each system.
- (viii) A list of links from inputs to mishaps for each system.

In addition, the application displays the results of the network analysis to the user through both text and graphics. A screen shot of the hazard display is shown in Figure 31.

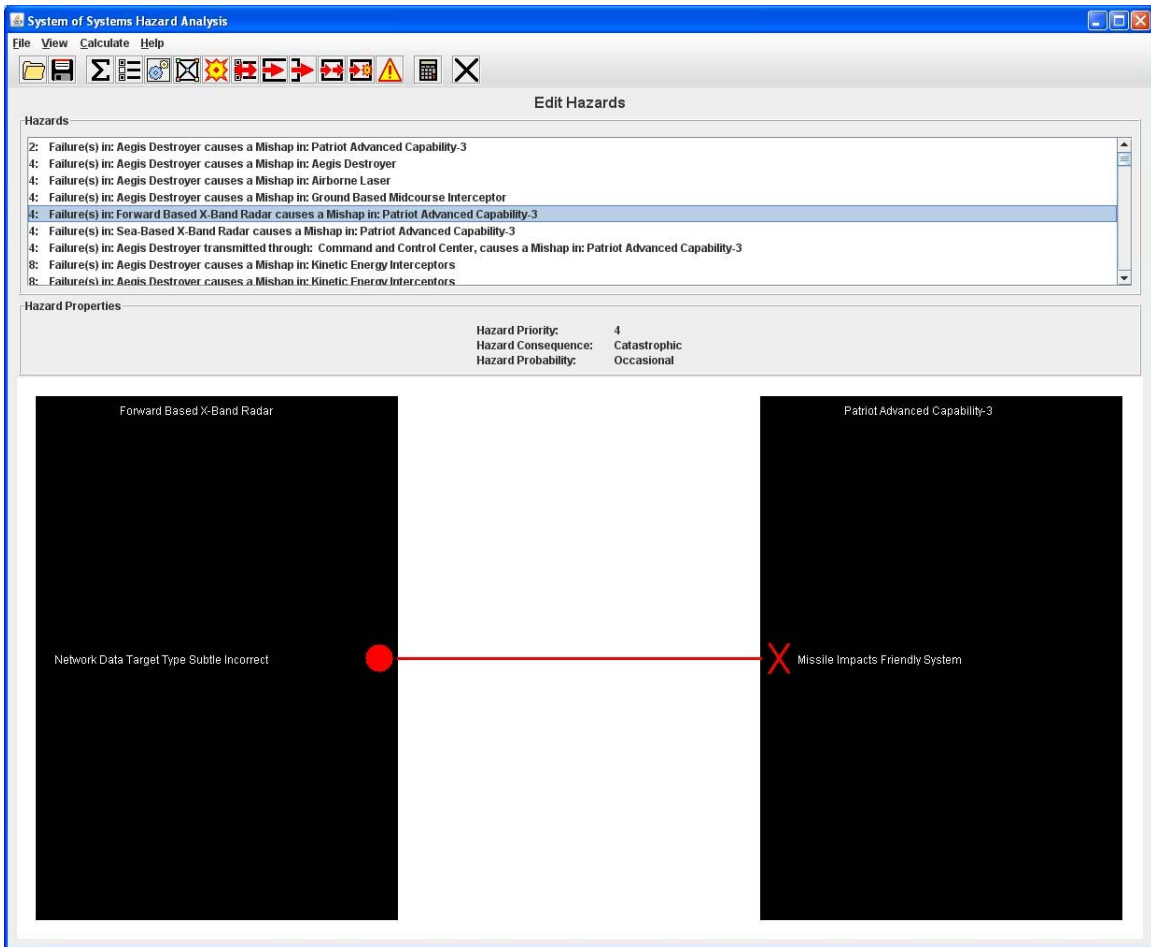


Figure 31. Interface Hazard Analysis Application Screen Shot – Hazard Display

Overall, the interface hazard analysis application is not a particularly complex application. The majority of the application deals with data entry and storage. The application was developed over a period of two months and consists of approximately 5,500 lines of code. Although its operation was successfully verified with test data, the application will also be tested on the Ballistic Missile Defense System case study.

C. SYSTEM OF SYSTEMS HAZARD ANALYSIS

1. Overview

The Ballistic Missile Defense System employs systems of systems technology to achieve a complex mission within a hazardous environment and as

such, is ideal for validating the interface hazard analysis technique. The data that will be used to perform this validation has been generated from the functional roles of the systems that comprise the system of systems and may or may not be representative of actual system performance. In addition, the system data has been simplified to reduce the time taken to perform the analysis to a manageable level. Neither of these facts affects the validity of the case study.

2. System of Systems Architecture

The systems that comprise the system of systems are shown in Table 8.

Symbol	System	Role
S ₁	Aegis Destroyer	Sensor and Weapon System
S ₂	Airborne Laser	Sensor and Weapon System
S ₃	Command and Control Center	CandC
S ₄	Forward-based X-Band Radar	Sensor
S ₅	Ground-based Midcourse Interceptors	Weapon
S ₆	Kinetic Energy Interceptors	Weapon
S ₇	Multiple Kill Vehicles	Weapon
S ₈	Patriot Advanced Capability-3	Weapon
S ₉	Sea-based X-Band Radar	Sensor
S ₁₀	Space-based Sensors	Sensor
S ₁₁	Terminal High Altitude Area Defense	Weapon

Table 8. Ballistic Missile Defense System Component Systems

These systems interact as shown in Table 9.

	S ₁	S ₂	S ₃	S ₄	S ₅	S ₆	S ₇	S ₈	S ₉	S ₁₀	S ₁₁
S ₁	m:n	n:1	m:n	m:n	m:n	m:n	m:n	m:n	n:1	-	m:n
S ₂	1:n	-	1:n	1:n	-	-	-	-	1:1	-	-
S ₃	m:n	n:1	m:n	m:n	m:n	m:n	m:n	m:n	n:1	m:n	m:n
S ₄	m:n	n:1	m:n	m:n	m:n	m:n	m:n	m:n	n:1	-	m:n
S ₅	m:n	-	m:n	m:n	-	-	-	-	n:1	-	-
S ₆	m:n	-	m:n	m:n	-	-	-	-	n:1	-	-
S ₇	m:n	-	m:n	m:n	-	-	-	-	n:1	-	-
S ₈	m:n	-	m:n	m:n	-	-	-	-	n:1	-	-
S ₉	1:n	1:1	1:n	1:n	1:n	1:n	1:n	1:n	-	-	1:n
S ₁₀	-	-	m:n	-	-	-	-	-	-	-	-
S ₁₁	m:n	-	m:n	m:n	-	-	-	-	n:1	-	-

Table 9. Ballistic Missile Defense System Architecture Table

3. System Models

Development of the system models starts with identification of transmission paths, message types, message names and analysis guide words. The possible transmission paths are shown in Table 10. The message types are shown in Table 11 and message names in Table 12. The guide words and their definition are shown in Table 13.

Transmission Paths
Network
Voice

Table 10. Ballistic Missile Defense System Transmission Paths

Message Types
Command
Data
Response

Table 11. Ballistic Missile Defense System Message Types

Message Names	Message Meaning
Cue	Command a sensor system to track a target
Fire	Command a weapon system to fire on a target
System Location	The geographic location of the transmitting system
System Status	The status of the transmitting system
Target Detected	Communicate that a target has been detected
Target Track	A data set that describes the ballistic path of a target
Target Type	The type of target that has been detected

Table 12. Ballistic Missile Defense System Message Names

Guide Word	Meaning
None	Intended result not achieved.
More	Too much of some parameter.
Less	Not enough of a parameter.
As Well As	Unintended activity or material.
Part Of	Parts of the parameter are missing.
Reverse	Value is opposite of intended value.
Other Than	Something other than intended result happens.
Omission	Intended output missing.
Commission	Unintended output.
Early	Output occurs too soon.
Late	Output occurs too late.
Coarse Incorrect	Output's value is wrong.
Subtle Incorrect	Output's value is wrong, but cannot be detected.

Table 13. Guide Words for Input and Output Analysis

The next step is to define a list of mishaps for all systems. These mishaps can be obtained from the system hazard analysis. An example mishap list for the Aegis Destroyer is shown in Table 14. The complete list for all systems is shown in Appendix D, Table 25.

System	Mishap	Consequence
Aegis Destroyer	Radiation causes harm to personnel	Critical
	Radiation causes harm to property	Critical
	Missile exhaust causes harm to personnel	Critical
	Missile impacts friendly system	Catastrophic
	Missile impacts friendly building	Catastrophic
	Missile impacts friendly terrain	Marginal
	Missile impacts hostile terrain	Negligible

Table 14. Mishap List for the Aegis Destroyer

The inputs and outputs for each system are shown in Appendix D Table 26 and Table 27, respectively. This data can be collected from system design documentation (such as Interface Design Descriptions) and the system of systems network specification. For the purposes of an input or output analysis, it is necessary to collate this data into a single, usable source so that each input or output can be systematically analyzed using the guide words. Note that the inputs and outputs are formed from the defined transmission paths, message types and message names.

Once the system inputs and the guide words have been defined, the input analysis can be performed. For each system input, apply each guide word and determine the effects on system mishaps and outputs. For example, within the Forward-based X-Band Radar System, the input “Network Data Cue” and the guide word “None” combine to form the input failure “Network Data Cue None”. This type of input failure does not cause a system mishap, nor does it cause a

system output to fail. However, the same input, when combined with the “Commission” guide word may lead to a system mishap if the cueing of the radar system causes personnel in front of the antenna to be exposed to radiation. The result of this is a link from the input “Network Data Cue Commission” to the mishap “Radiation Causes Harm to Personnel”. Within the Command and Control System, the input “Network Data Target Track” combined with the guide word “Subtle Incorrect” leads to a dependent output failure “Network Data Target Track Subtle Incorrect”. This is a link from an input to an output. The full list of system input to mishap and input to output links are shown in Appendix D Table 28 through Table 42. Together, these tables describe the system models for each of the systems within the Ballistic Missile Defense System.

4. Preliminary Hazard List

The system model data was entered into the interface hazard analysis application and a network analysis performed. Note that the application can only detect a limited number of a interface hazard schemes due to the abridged version of the network analysis algorithm. From the system model data, the application detected 364 interface hazards ranging from priority two to priority twenty. Some selected hazards are shown in Table 15. From these results, it is clear that the interface hazard analysis technique, and the interface hazard analysis application, are both capable of detecting interface hazards. The application should be developed further in order to be usefully applied to a full scale system of systems.

Hazard	Probability	Consequence	Priority
<p>Network Data Target Type Subtle Incorrect failure in Aegis Destroyer causes</p> <p>Missile Impacts Friendly System mishap in Patriot Advanced Capability-3</p>	Probable	Catastrophic	2
<p>Network Data Target Track Subtle Incorrect failure in Forward-based X- Band Radar causes</p> <p>Missile Impacts Friendly Building mishap in Kinetic Energy Interceptors</p>	Remote	Catastrophic	8
<p>Network Data Target Type Subtle Incorrect failure in Airborne Laser causes</p> <p>Network Data Target Type Subtle Incorrect failure in Command and Control Center causes</p> <p>Missile Impacts Friendly System mishap in Aegis Destroyer</p>	Remote	Catastrophic	8
<p>Network Data Target Detected Commission failure in Airborne Laser causes</p> <p>Network Command Cue Commission failure in Command and Control Center causes</p> <p>Radiation Causes Harm to Personnel mishap in Sea-based X-Band Radar</p>	Remote	Critical	10

Table 15. Selected Interface Hazards from the Ballistic Missile Defense System Case Study

From the analysis, it is clear that the most significant hazard within the Ballistic Missile Defense System is the incorrect designation of a target as a threat (Network Data Target Type Subtle Incorrect) when it is in fact a friendly system. This has occurred on several occasions with the Patriot system that confused low flying aircraft with cruise missiles. It is possible that the Ballistic Missile Defense System may misidentify aircraft or rockets carrying a non-threatening payload (particularly from China or Russia) as a threat. Any resultant destruction of such a system could be catastrophic. However, it is likely that the Missile Defense Agency has already taken this into account, and begun to mitigate the hazard. What the interface hazard analysis does reveal is the large number of ways in which such a mishap can occur.

5. System of Systems Evolution

To demonstrate the ability of the interface hazard analysis technique to deal with system of systems evolution, a mythical “Advanced Technology System” was added to the system of systems network. The Advanced Technology System is a detection system that detects launches of ballistic missiles. It does not provide track data accurate enough for a launch, it only detects launches and gives the general location. It interfaces only with the Command and Control Center and there are a large number of devices. It is a passive system, and hence there are only minor mishaps associated with it.

In adding the Advanced Technology System to the system of systems, only its system model was added. None of the other system models were altered in anyway. The system model consists of just one failed output: Network Data Target Detected Commission with probability: Remote.

When the network analysis was run again, eighteen extra hazards were identified. These hazards involved other systems, demonstrating the interface hazard analysis technique successfully identifies new hazards when new systems are added without altering current system models. An example hazard is shown in Table 16.

Hazard	Probability	Consequence	Priority
Network Data Target Detected Commission failure in Advanced Technology System causes Network Command Fire Commission failure in Command and Control Center causes Missile Exhaust Causes Harm to Personnel failure in Ground-based Midcourse Interceptor	Remote	Critical	10

Table 16. Example Hazard following the addition of the Advanced Technology System

D. LESSONS LEARNT

A significant result of this case study is the large number of hazards that are identified from a relatively small set of systems, each with a restricted set of inputs and outputs. In particular, a large number of hazards are very similar. This is due to the types of systems present in the Ballistic Missile Defense System, which perform the role of a sensor, a weapon or both. The application should be modified to group similar hazards together to ensure that all hazard types receive adequate visibility.

In addition, while the generation of a simple, linear system model is not particularly onerous, the system models can become difficult to generate and comprehend when dealing with multiple input failures leading to multiple outputs or mishaps. For example, if there are ten inputs and ten guide words then there are 100 single input/guide words combinations. When considering two inputs, there are 9,000 combinations, when considering three, there are 720,000 combinations. This makes it very difficult to ensure that the system models are complete.

E. CONCLUSION

Both the interface hazard analysis technique and the interface hazard analysis application were successful in detecting Ballistic Missile Defense System interface hazards. Although the application employed a limited network analysis technique, it was still able to detect a significant number of interface hazards. The concept of a software application that can detect interface hazards using the interface hazard analysis technique was successfully demonstrated.

In addition, the interface hazard analysis technique proved both useable and effective. The system models that were required were not difficult to generate, even from a basic understanding of the Ballistic Missile Defense System. The input and output analyses were relatively simple to perform, although it may be more difficult to identify links that involve multiple inputs or outputs when the number of inputs and outputs are expanded beyond the modest set used in this case study.

In all, both the interface hazard analysis technique and the concept of a software application to employ this technique should be considered effective.

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VI. CONCLUSION

A. KEY FINDINGS AND ACCOMPLISHMENTS

The existence of systems of systems hazards, and in particular emergent hazards, has been acknowledged since the first systems of systems were conceived. In this thesis, the types of emergent hazards have been identified and defined. Systems of systems hazards can be broken down into two main categories. Single system hazards are those that are attributable to a single system only and require no system interaction in order to occur, and emergent hazards are those that require the interaction of two or more systems.

Emergent hazards were the focus of this research. System hazard analysis techniques are largely unable to identify emergent hazards. New techniques must be developed to identify and analyze emergent hazards. Before this can be done, the types of emergent hazards must be further defined. There are three sub categories of emergent hazards. Reconfiguration hazards are unique to systems of systems and do not have a parallel within the system space. They are caused by the transition of a system of systems from one state to another. Interoperability hazards result from miscommunications. A receiving system interprets a message or signal in a manner that conflicts with the intent of the transmitting system. The third subcategory is integration hazards. These hazards can best be described by the subtypes of the category. There are three subtypes, interface hazards, resource hazards and proximity hazards. An interface hazard results from a failure or partial performance in one system causing a mishap in a second system. A resource hazard occurs when there are insufficient levels of shared resources to support the systems present, or when there is a conflict over a certain part of the shared resource. A proximity hazard occurs when one system causes a mishap in another without using a defined interface.

The purpose of identifying the types of emergent hazards is to focus the development of hazard analysis techniques. In this thesis, a process was defined

that specifically targets interface hazards. This is a small part of the puzzle. A full system of systems hazard analysis must address all hazard types. Other techniques must be used in conjunction with the interface hazard analysis technique defined in this thesis.

The interface hazard analysis technique is based upon the Input/Output/Mishap (IOM) system model. The IOM model is an extension of the more traditional Input/Output (IO) model. An interface hazard consists of not just inputs and outputs but mishaps as well. The IOM model for a system is a set of links between inputs and outputs, links between inputs and mishaps, and outputs that can fail due to a system failure. These three elements can be used to construct an interface hazard. They form a path for a system failure, which may otherwise be innocuous, to transfer to another system where it may cause a mishap.

The interface hazard analysis technique has two important characteristics. Firstly, the system model is relatively simple and quick to develop. System models can be extremely complex, and hence expensive to create. A simple but effective system model is essential to ensure a cost effective hazard analysis. The IOM model meets this requirement. Additionally, the interface hazard analysis technique must be able to keep pace with the evolution of the system of systems. The interface hazard analysis technique achieves this by using system models that are independent of other systems and an automated search process. In the event that a system is added, removed or modified, only that system model needs to be added, removed or modified; all other system models can remain the same.

The technique also provides methods for assessing mishap risk and estimating the residual risk. The mishap risk is a function of its component elements, each of which has its own probability. The probabilities are assessed qualitatively, and combined using a qualitative probability scheme. The assessment of risk in this manner allows interface hazards to be compared directly with hazards identified by other techniques.

The size of a system of systems in combination with its virtually infinite configurations makes it impractical to conduct a complete system of systems hazard. For interface hazards, the residual mishap risk was assessed by considering known hazards, limiting the probability of unidentified hazards, and minimizing unknowns through effective techniques and qualified practitioners.

Finally, a software application was developed for use in proving that the interface hazard analysis technique is valid. The software application was developed in a relatively short period of time and was relatively small in nature, but was successfully applied to the Ballistic Missile Defense System and successfully identified interface hazards.

B. FUTURE WORK

There are two major areas for further research. Firstly, the system of systems hazard taxonomy is not complete. There are other types of emergent hazards. This taxonomy needs to be further expanded and defined. The follow on from this is that techniques must be developed that identify and analyze each of these hazard types. This thesis proposes a technique for identifying only one hazard type. At the very least, four more hazard analysis techniques are required, though it may be possible that one technique could cover more than one hazard type.

An assumption that was made regarding system of systems hazard analysis is that the analysis will never provide full coverage. That is, there are parts of a system of systems that will never be analyzed. Considering that there will be several hazard analysis techniques, and limited budgets, a decision may be required to perform one technique and not another. Such a decision should be based upon an assessment of which technique is most likely to identify the highest priority hazards. A method for determining the most effective technique for a given application should also be developed.

The success of the interface hazard analysis technique depends largely upon the guide words that are used. A robust and proven set of guide words should be developed to ensure more accurate system models.

In addition, while the interface hazard analysis technique is capable of detecting hazards, this data needs to be integrated into the system safety requirements traceability matrix.

A promising area of research is the application of formal specifications to system interfaces.³⁹ These techniques may provide methods for preventing or resolving system of systems interface hazards.

³⁹ D.S. Caffal, and J.B. Michael, (2005) Formal Methods in a System-of-Systems Development. *IEEE International Conference on Systems, Man and Cybernetics*. pp. 1856-1863.

APPENDIX A. INTERFACE HAZARD ANALYSIS TECHNIQUE

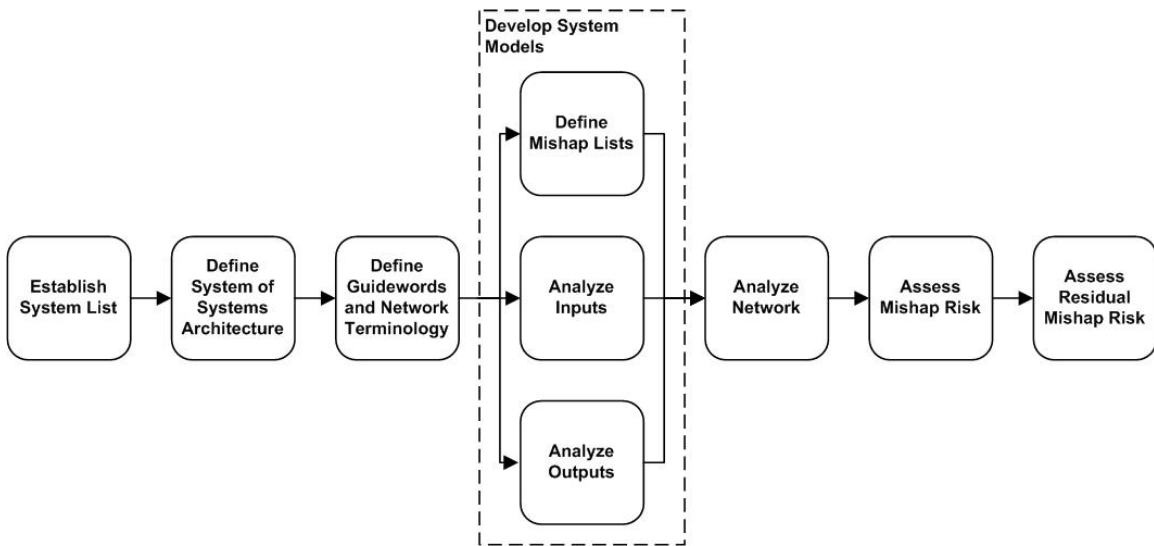


Figure 32. The Interface Hazard Analysis Technique

Establish System List

1. List all systems that may be part of the system of systems.

Define System of Systems Architecture

2. For each system pair, identify the connection that may occur as one of:

- (i) One to One (1:1)
- (ii) One to Many (1:n)
- (iii) Many to One (n:1)
- (iv) Many to Many (m:n)

Define Guidewords and Network Terminology

3. Define a standardized list of network terminology. Describe all system inputs and outputs in these terms. The network terminology should include options for each of the following:

- (i) Transmission Path⁴⁰
- (ii) Message Type (e.g. data, command)
- (iii) Message Name

4. Define a list of guidewords that will be used to assess the inputs and outputs of a system. The guidewords describe the failures that the inputs and outputs may suffer. A quality set of guidewords is essential to the success of the technique.

Define Mishap Lists

- 5. List all mishaps for each system.

Analyze Inputs

- 6. List all inputs for each system using the network terminology.
- 7. For each input, apply each guideword and determine the effect of the resultant failure on the outputs of the system. Consider multiple inputs as causes for single output failures and single input failures causing multiple output failures. If a link can be found, add it to the system model. Assess the probability of the link occurring. That is, the probability that the output failure occurs given that the input failure has occurred.

8. For each input, apply each guideword and determine whether the resultant failure can cause one of the system mishaps. Consider multiple inputs combining to cause a mishap. If a link can be found, add it to the system model. Assess the probability of the link occurring, that is, the probability that the mishap will occur given that the input failure has occurred.

Analyze Outputs

- 9. For each output, apply each guideword and determine whether the resultant failure can be caused by a failure within the system. Consider multiple output failure occurring from a single set of system failures. Add all output

⁴⁰ All transmission paths must be considered, including in-band paths (e.g., defined interfaces) and out-band paths (e.g., voice communication to subvert system checks).

failures to the system model. Assess the probability of the output failure occurring, that is, the probability of the necessary system failures occurring and the probability of the system failures leading to the output failure.

Analyze Network

10. For each system, assemble a system model that consists of all identified:

- (i) Links between input failures and outputs failures,
- (ii) Links between input failures and mishaps, and
- (iii) Output failures caused by internal system failures.

11. Construct a network analysis tree for each link between an input failure and a mishap. Assemble the tree out of links between input failures and output failures, and output failures caused by internal system failures. Continue constructing the tree until all tree branches terminate in an output failure caused by an internal system failure or to sufficient depth such that any hazards that remain unidentified have a maximum probability that is acceptable.

12. Summarize the network analysis by creating a list of all identified interface hazards.

Assess Mishap Risk

13. Construct a table that applies the AND function to two qualitative probability levels.

14. For each identified interface hazard, assess the mishap risk in terms of probability and consequence. Use the probabilities of the individual interface hazard elements and the qualitative probability combination table in order to calculate the overall probability.

Assess Residual Mishap Risk

15. Once all risk mitigation activities have been conducted, assess the residual mishap risk in the system of systems due to interface hazards. Consider the following in the assessment:

- (i) Risk due to identified hazards,
- (ii) Risk due to hazards not covered by the extent of the network trees, and
- (iii) Risk due to hazards not identified due to shortfalls in the system models.

Report Results

10. Link the resultant artifacts from the hazard analysis back to the system safety requirement traceability matrix.

APPENDIX B. QUALITATIVE PROBABILITY COMBINATIONS

The Hazard Analysis process requires that engineers assign a qualitative value to the likelihood of an events occurrence. When dealing with a System of Systems, these events can be combined to form a single hazard. The probability of the hazard is a function of the probabilities of the component events. As each event is required for the hazard to occur, the probability of the hazard is assessed using the AND function. This appendix outlines how qualitative probabilities may be combined using the AND function.

The probability of the hazard is defined as:

$$P(\text{Hazard}) = P(\text{Event}_1) \text{ AND } P(\text{Event}_2) \text{ AND } \dots \text{ AND } P(\text{Event}_n)$$

Each event is assigned a qualitative probability in accordance with MIL-STD-882D. Qualitative probabilities are used because of the expense and difficulty of obtaining quantitative probabilities. The purpose of this assessment is to determine whether relative probability, that is whether one hazard has a higher probability than another, not absolute probability.

Table 17 shows the qualitative probability levels from MIL-STD-882D. Columns (I) and (II) are taken directly from MIL-STD-882D. The description of each level includes a loose mathematical definition. The definition is not complete because it does not adequately describe the boundaries between probabilities. For example, it is unclear what the probability level would be for an event with probability 10^{-1} . Column (III) has been added to indicate the two methods that can be used to fully define the spectrum of probabilities. A probability value on the boundary can either be assigned to the higher or lower probability level. Although the distinction may appear insignificant, a strict definition is important when combining qualitative probabilities automatically.

(I) Name	(II) MIL-STD-882D Definition	(III) Strict Definition
Frequent	Likely to occur often within the life of an item, with a probability of occurrence greater than 10^{-1} in that life.	$1 \geq P > 10^{-1}$ or $1 \geq P \geq 10^{-1}$
Probable	Will occur several times within the life of an item, with a probability occurrence less than 10^{-1} but greater than 10^{-2} in that life.	$10^{-1} \geq P > 10^{-2}$ or $10^{-1} > P \geq 10^{-2}$
Occasional	Likely to occur sometime in the life of an item, with a probability of occurrence less than 10^{-2} but greater than 10^{-3} in that life.	$10^{-2} \geq P > 10^{-3}$ or $10^{-2} > P \geq 10^{-3}$
Remote	Unlikely but possible to occur in the life of an item, with a probability of occurrence less than 10^{-3} but greater than 10^{-6} in that life.	$10^{-3} \geq P > 10^{-6}$ or $10^{-3} > P \geq 10^{-6}$
Improbable	So unlikely, it can be assumed occurrence may not be experienced, with a probability of occurrence less than 10^{-6} in that life.	$10^{-6} \geq P \geq 0$ or $10^{-6} > P \geq 0$

Table 17. MIL-STD-882D Mishap Probability Levels⁴¹

There are six options for interpreting a qualitative probability numerically in order to combine with another qualitative probability and then map the result back to a qualitative probability. Each qualitative probability can be interpreted either as a worst case scenario, i.e., at the upper limit of the range, or a best case scenario at the lower limit of the range, or at some point between the two. When interpreting limits and mapping the result back to a qualitative probability, the limits can be interpreted conservatively and boundary probabilities assigned to the higher probability level, or optimistically and boundary probabilities

⁴¹ MIL-STD-882D *Standard Practice for System Safety* (2000) §A.4.4.3.2.2.

assigned to the lower probability level. The result of each option is a table that details the result of applying the AND function to two qualitative probability levels.

For example, using the optimistic interpretation, Frequent AND Probable results in:

$$\begin{aligned} & (1 \geq P_1 > 10^{-1}) \times (10^{-1} \geq P_2 > 10^{-2}) \\ & 1 \times 10^{-1} \geq P_1 \times P_2 > 10^{-1} \times 10^{-2} \\ & 10^{-1} \geq P_1 \times P_2 > 10^{-3} \end{aligned}$$

Thus, the combination of Frequent AND Probable results in a probability ranging from, but not including, 10^{-3} up to and including 10^{-1} . At the low end, a probability of just greater than 10^{-3} maps to a qualitative probability level of Occasional. At the high end, with a probability of 10^{-1} , the probability level is Probable. This process can be repeated for each interpretation of the MIL-STD-882D limits to produce the upper and lower bounds shown in Table 18.

In addition to the boundary conditions, a middle value may also be considered. That is, a value that is equally spaced between the upper and lower bounds of the probability level. Table 19 shows the middle values that will be used to analyze the middle ground of qualitative probability combinations. These middle values are then combined in Table 20. The interpretation of the values in Table 20 will depend upon whether the MIL-STD-882D limits are interpreted optimistically or conservatively.

AND	Frequent	Probable	Occasional	Remote	Improbable
Frequent	$1 \geq P > 10^{-2}$ or $1 \geq P \geq 10^{-2}$	$10^{-1} \geq P > 10^{-3}$ or $10^{-1} > P \geq 10^{-3}$	$10^{-2} \geq P > 10^{-4}$ or $10^{-2} > P \geq 10^{-4}$	$10^{-3} \geq P > 10^{-7}$ or $10^{-3} > P \geq 10^{-7}$	$10^{-6} \geq P \geq 0$ or $10^{-6} > P \geq 0$
Probable	$10^{-1} \geq P > 10^{-3}$ or $10^{-1} > P \geq 10^{-3}$	$10^{-2} \geq P > 10^{-4}$ or $10^{-2} > P \geq 10^{-4}$	$10^{-3} \geq P > 10^{-5}$ or $10^{-3} > P \geq 10^{-5}$	$10^{-4} \geq P > 10^{-8}$ or $10^{-4} > P \geq 10^{-8}$	$10^{-7} \geq P \geq 0$ or $10^{-7} > P \geq 0$
Occasional	$10^{-2} \geq P > 10^{-4}$ or $10^{-2} > P \geq 10^{-4}$	$10^{-3} \geq P > 10^{-5}$ or $10^{-3} > P \geq 10^{-5}$	$10^{-4} \geq P > 10^{-6}$ or $10^{-4} > P \geq 10^{-6}$	$10^{-5} \geq P > 10^{-9}$ or $10^{-5} > P \geq 10^{-9}$	$10^{-8} \geq P \geq 0$ or $10^{-8} > P \geq 0$
Remote	$10^{-3} \geq P > 10^{-7}$ or $10^{-3} > P \geq 10^{-7}$	$10^{-4} \geq P > 10^{-8}$ or $10^{-4} > P \geq 10^{-8}$	$10^{-5} \geq P > 10^{-9}$ or $10^{-5} > P \geq 10^{-9}$	$10^{-6} \geq P > 10^{-12}$ or $10^{-6} > P \geq 10^{-12}$	$10^{-9} \geq P \geq 0$ or $10^{-9} > P \geq 0$
Improbable	$10^{-6} \geq P \geq 0$ or $10^{-6} > P \geq 0$	$10^{-7} \geq P \geq 0$ or $10^{-7} > P \geq 0$	$10^{-8} \geq P \geq 0$ or $10^{-8} > P \geq 0$	$10^{-9} \geq P \geq 0$ or $10^{-9} > P \geq 0$	$10^{-12} \geq P \geq 0$ or $10^{-12} > P \geq 0$

Table 18. Qualitative Probability Combinations - Limits

Level	Lower Limit	Upper Limit	Middle Value
Frequent	10^{-1}	10^0	$10^{-0.5}$
Probable	10^{-2}	10^{-1}	$10^{-1.5}$
Occasional	10^{-3}	10^{-2}	$10^{-2.5}$
Remote	10^{-6}	10^{-3}	$10^{-4.5}$
Improbable	0	10^{-6}	$10^{-7.5}$

Table 19. Qualitative Probability Levels – Middle Values

AND	Frequent	Probable	Occasional	Remote	Improbable
Frequent	10^{-1}	10^{-2}	10^{-3}	10^{-5}	10^{-8}
Probable	10^{-2}	10^{-3}	10^{-4}	10^{-6}	10^{-9}
Occasional	10^{-3}	10^{-4}	10^{-5}	10^{-7}	10^{-10}
Remote	10^{-5}	10^{-6}	10^{-7}	10^{-9}	10^{-12}
Improbable	10^{-8}	10^{-9}	10^{-10}	10^{-12}	10^{-15}

Table 20. Qualitative Probability Combinations – Middle Values

The data now exists for six tables that define six different interpretations of the MIL-STD-882D probability levels. However, when the results of the boundary conditions are compared back to either the conservative or optimistic interpretations of the probability ranges, the differences resolve themselves and the qualitative probability combination tables become identical. As such, there are only four possible tables. The choice of one particular table for use within a specific application is a judgment call that must be made within a specific system safety context. However, each of the tables is distinguishable in terms of the average probability level of the results. Each table has the same level of input, that is, the same twenty-five probability combinations are used for all four tables.

The average probabilities of the outputs of each table can then be used to determine whether one table is more conservative or optimistic than another, which will aid the choice of table for a specific application. If the application places a large emphasis on safety, a more conservative table should be chosen. To compute the average probability, each probability level is assigned a numeric value (1 for Improbable through 5 for Frequent). The higher the average probability, the more conservative the table is. The four possible tables are shown in Table 21 through Table 24 and are shown in order from the most optimistic to the most conservative.

AND	Frequent	Probable	Occasional	Remote	Improbable
Frequent	Probable	Occasional	Remote	Improbable	Improbable
Probable	Occasional	Remote	Remote	Improbable	Improbable
Occasional	Remote	Remote	Remote	Improbable	Improbable
Remote	Improbable	Improbable	Improbable	Improbable	Improbable
Improbable	Improbable	Improbable	Improbable	Improbable	Improbable

Table 21. Qualitative Probability Combinations – Lower Limit – Average Risk 1.52

AND	Frequent	Probable	Occasional	Remote	Improbable
Frequent	Probable	Occasional	Remote	Remote	Improbable
Probable	Occasional	Remote	Remote	Improbable	Improbable
Occasional	Remote	Remote	Remote	Improbable	Improbable
Remote	Remote	Improbable	Improbable	Improbable	Improbable
Improbable	Improbable	Improbable	Improbable	Improbable	Improbable

Table 22. Qualitative Probability Combinations – Middle Values, Optimistic Interpretation – Average Risk 1.60

AND	Frequent	Probable	Occasional	Remote	Improbable
Frequent	Frequent	Probable	Occasional	Remote	Improbable
Probable	Probable	Occasional	Remote	Remote	Improbable
Occasional	Occasional	Remote	Remote	Improbable	Improbable
Remote	Remote	Remote	Improbable	Improbable	Improbable
Improbable	Improbable	Improbable	Improbable	Improbable	Improbable

Table 23. Qualitative Probability Combinations – Middle Values, Conservative Interpretation – Average Risk 1.92

AND	Frequent	Probable	Occasional	Remote	Improbable
Frequent	Frequent	Probable	Occasional	Remote	Improbable
Probable	Probable	Occasional	Remote	Remote	Improbable
Occasional	Occasional	Remote	Remote	Remote	Improbable
Remote	Remote	Remote	Remote	Improbable	Improbable
Improbable	Improbable	Improbable	Improbable	Improbable	Improbable

Table 24. Qualitative Probability Combinations – Upper Limit – Average Risk 2.00

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APPENDIX C. BALLISTIC MISSILE DEFENSE SYSTEM OVERVIEW

A. OVERVIEW

In order to explore the nature of systems of systems hazards and to validate any hazard analysis techniques in a practical manner, a case study is required. For the purposes of this research, the Ballistic Missile Defense System will be used to demonstrate hazard types and to assess hazard analysis techniques.

The ballistic missile defense program was initiated in 2002 in response to the threat posed by several developing nations that possessed simple, single warhead intercontinental ballistic missiles. An evolutionary acquisition strategy has been employed and the scope of the program has grown to include all types of ballistic missile threats. The composition of the Ballistic Missile Defense System will grow and change in the coming years as new systems are acquired and integrated.

The Ballistic Missile Defense System is a true system of systems. It employs a variety of systems in a distributed network that cooperate to complete system of systems goal. The state of the system of systems can change dynamically as systems either join the network, or depart to perform other roles. The Ballistic Missile Defense System is arguably the largest, most complex and most expensive defense program ever undertaken.

B. PURPOSE

According to the Missile Defense Agency:

[t]he fundamental objective of the Ballistic Missile Defense program is to develop the capability to defend forces and territories of the United States, its allies and friends against all classes and ranges of ballistic missile threats.⁴²

⁴² *BMD Basics – Overview* Retrieved February 27, 2007 from <http://www.mda.mil/mdalink/html/basics.html>.

The operational concept for the Ballistic Missile Defense System is a layered defense that provides the capability to strike against ballistic missiles in the boost, midcourse and terminal phases. At each phase, the commander of the Ballistic Missile Defense System has several options for destroying the threat ballistic missile.⁴³ The layered defense structure is shown in Figure 33.

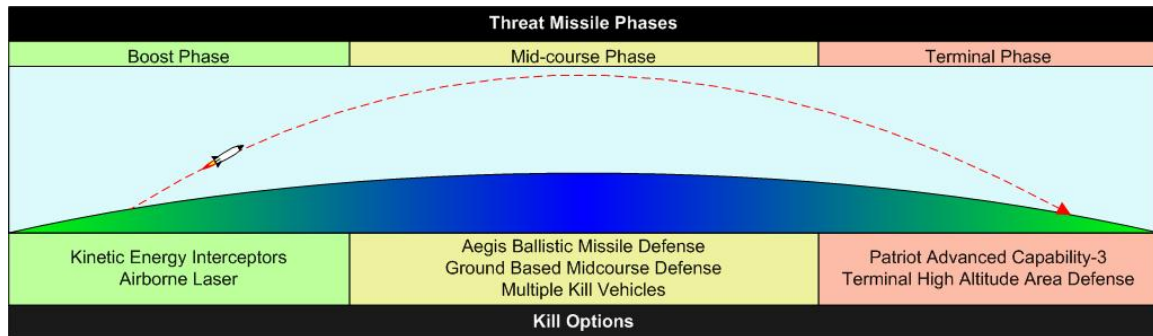


Figure 33. Ballistic Missile Defense System Layered Defense Structure⁴⁴

Each of the threat missile phases presents different challenges and advantages. In the boost phase, the missile is at its lowest velocity (it may even be stationary) and is hence easiest to hit. However, launch sites of the threat missile can vary greatly geographically and the missile does not remain in the boost phase for long, requiring an early detection and a rapid response. During the midcourse phase, the missile is moving significantly faster than during the boost phase, but the altitude of the missile means that collateral damage is highly unlikely and hence less discriminate weapons can be used. In the terminal phase, the missile is moving faster still, but the location of the missile is geographically restricted to the location of the United States, its allies and their forces. No phase represents the optimal solution, each has significant challenges. As such, the Ballistic Missile Defense System aims to engage threat missiles in all phases of flight.

⁴³ Missile Defense Agency. (2005). *A Day in the Life of the BMDS* (3rd Ed).

⁴⁴ After Ibid.

C. SYSTEM OF SYSTEMS ARCHITECTURE

The architecture of the Ballistic Missile Defense System is fairly simple. It employs a range of sensors and engagement options that are paired by several command and control centers. There is no rigid structure, and the network permits any sensor to be linked to any engagement option. This architecture is shown in Figure 34.

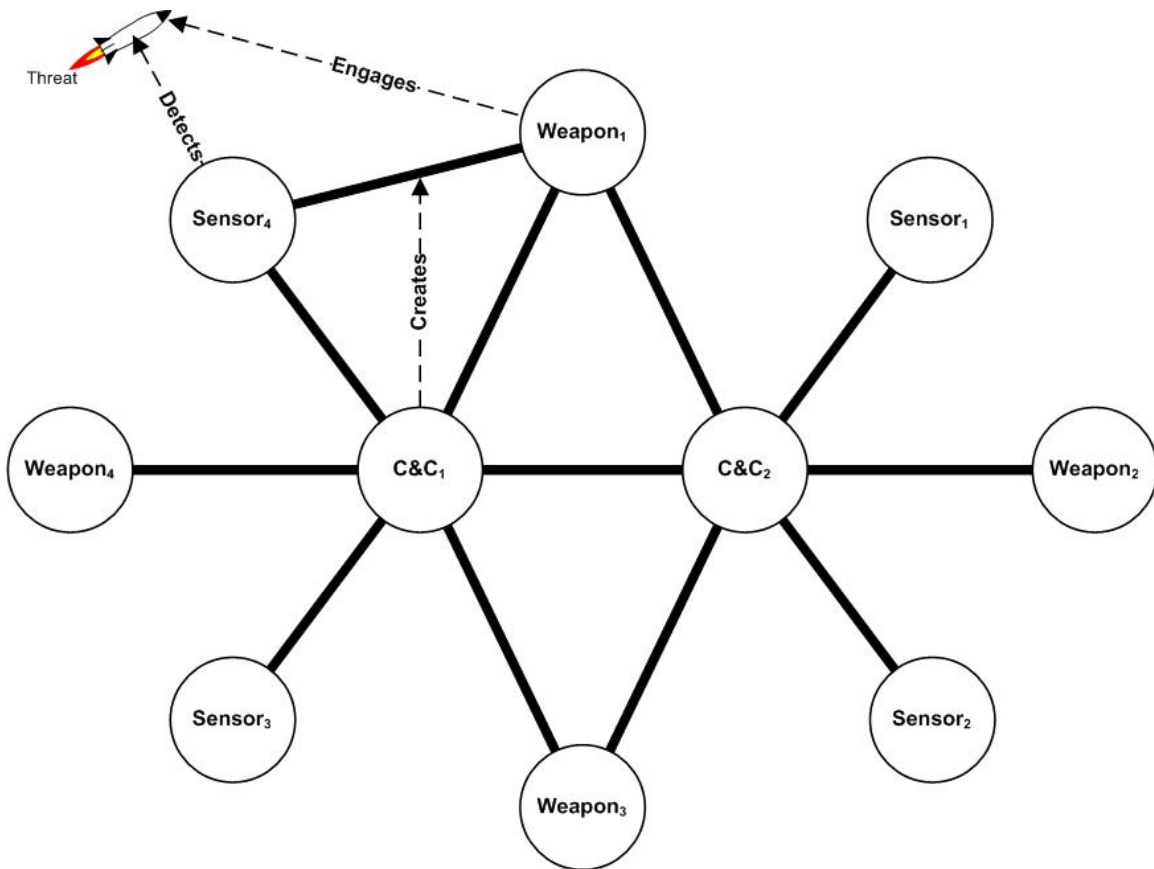


Figure 34. Ballistic Missile Defense System Architecture

In the architecture shown in Figure 34, there are four sensor systems and four weapon systems that integrate into the Ballistic Missile Defense System through two command and control centers. Some weapon systems, Weapon₁ and Weapon₃, are linked to both command and control centers, the other systems are linked to only one center. In the example shown, Sensor₄ detects

the threat missile and notifies CandC₁. CandC₁ allocates Weapon₁ to engage the threat missile, and creates a link between Weapon₁ and Sensor₄. This is an overly simplified example, the threat missile is likely to be detected by several

sensors, and several weapons will be assigned to engage the threat missile (at least one for each phase of flight), but it serves to show how the Ballistic Missile Defense System network is created and operates.

D. COMPONENT SYSTEMS

1. Command and Control, Battle Management and Communications

The Command and Control, Battle Management and Communications element is the backbone of the Ballistic Missile Defense System. Its purpose is to ensure the flow of critical information between system elements by tracking all potential ballistic missile threats, directing weapon systems to engage threat missiles and pairing weapons systems with sensor systems to engage threat missiles in all phases of flight. The Command and Control, Battle Management and Communications element consists of four major subsystems: Situational Awareness, Planner, Battle Management and Network. Together, these subsystems:

provide the Ballistic Missile Defense System with planning capability to optimally locate sensors and weapon systems to counter identified threats; situational awareness of the evolving battle and status of defensive assets at all leadership levels; sensor netting to detect identify, track and discriminate threats; global integrated fire control to pair the right sensors and weapon systems against multiple threats for the highest probability of kill and to best manage a relatively limited shot magazine; and global communications networks to efficiently manage and distribute essential data.⁴⁵

⁴⁵ Missile Defense Agency. (2005). *A Day in the Life of the BMDS* (3rd Ed), p. 15.



Figure 35. Command and Control, Battle Management and Communications Control Center⁴⁶

2. Aegis Ballistic Missile Defense

Aegis destroyers were originally developed to provide a forward air to surface capability for the protection of aircraft carriers, in particular to counter the air to surface anti-ship missile threat. They have been modified to perform the role of both sensor and weapon system within the Ballistic Missile Defense System. A Long Range Surveillance and Track capability is added to Aegis destroyers to allow Aegis to trigger other Ballistic Missile Defense System sensors, and to provide track data to ground-based midcourse defense elements. Aegis destroyers so equipped are forward deployed to extend the battle space and provide early warning.

In addition to their primary role as sensors, Aegis destroyers can be outfitted with the Standard Missile-3 which allows them to engage short and medium range ballistic missiles. This capability is currently considered an emergency capability only. The role of Aegis is expected to evolve and increase as new technologies are tested and employed.⁴⁷

⁴⁶ Missile Defense Agency. (2005). *A Day in the Life of the BMDS* (3rd Ed), p. 14.

⁴⁷ *Ibid.*, p. 17.



Figure 36. Aegis Ballistic Missile Defense⁴⁸

3. Airborne Laser

The airborne laser is a megawatt-class, chemical oxygen iodine laser mounted on a Boeing 747 aircraft that is capable of destroying ballistic missiles at a distance of several hundred kilometers. The airborne laser engages threat ballistic missiles in the boost phase only. In addition to its engagement capability, the airborne laser also carries six infrared sensors that are used to detect the heat plume from a ballistic missile launch. The airborne laser is also capable of receiving target coordinates from the command and control centers. At the time of writing, the laser had been successfully fired to sufficient power and duration on the ground, and the aircraft platform with the laser controls and sensors has been successfully test flown, but the full system has not been tested.⁴⁹

⁴⁸ From *Program Images* Retrieved February 27, 2007 from <http://www.mda.mil/mdalink/html/nmdimg.html#fm6.ANC>.

⁴⁹ Missile Defense Agency. (2005). *A Day in the Life of the BMDS* (3rd Ed), p. 19.



Figure 37. Airborne Laser⁵⁰

4. Forward-Based X-Band Radar

The Forward-Based X-Band Radar is used to detect ballistic missile threats and provide precise tracking information to the Ballistic Missile Defense System. It is able to track ballistic missiles in the boost phase, discriminate between threat and non-threat projectiles and pass track data to the Ballistic Missile Defense System for engagement by midcourse and terminal weapon systems. It can either scan autonomously or be cued by other sensor systems.⁵¹

⁵⁰ From *Program Images* Retrieved February 27, 2007 from <http://www.mda.mil/mdalink/html/nmdimg.html#fm6.ANC>.

⁵¹ Missile Defense Agency. (2005). *A Day in the Life of the BMDS* (3rd Ed), p. 21.



Figure 38. Forward-Based X-Band Radar⁵²

5. Ballistic Missile Defense System Space Systems

The Ballistic Missile Defense System will employ several space-based sensors, though this capability is limited at present. The intent of the space systems sensors is to employ infrared and optical sensors to track ballistic missile threats through all phases of flight and to hand off track data to command and control elements for threat missile engagement. In addition, the Missile Defense Agency is currently exploring the economic feasibility of deploying a space-based interceptor. Such a weapon would not be limited by geography like land, sea and air-based interceptors.⁵³

6. Ground-based Midcourse Defense

The ground-based midcourse defense system is designed to detect, track and engage intermediate and long range ballistic missiles in the midcourse phase of flight. Unlike other Ballistic Missile Defense System elements, the ground-based midcourse defense element is a command and control center, sensor and weapon system. It is able to engage ballistic missile threats without the support of the remaining elements, or it can provide sensor and weapon options to the larger system of systems. The ground-based midcourse defense

⁵² From Missile Defense Agency. (2005). *A Day in the Life of the BMDS* (3rd Ed), p. 20.

⁵³ *Ibid.*, p. 23.

element utilizes other system sensors as well as adding a sea-based X-band radar. A ground-based interceptor is used to engage ballistic missiles in the midcourse phase at high altitudes and speeds. The booster places an exoatmospheric kill vehicle on a collision path with the threat missile. The kill vehicle uses kinetic energy to destroy the incoming threat.⁵⁴

7. Terminal High Altitude Area Defense

The Terminal High Altitude Area Defense element provides a regional defense against threat ballistic missiles. It receives tracking data from the Ballistic Missile Defense System and is capable of launching a kinetic energy kill vehicle that can destroy ballistic missiles in all phases of flight, either within or just outside the atmosphere. The Terminal High Altitude Area Defense element also tracks the threat missile and guides the kill vehicle to impact.⁵⁵



Figure 39. Terminal High Altitude Area Defense⁵⁶

8. Multiple Kill Vehicles

Multiple kill vehicles are designed specifically to counter the threat of ballistic missiles with multiple, independent re-entry vehicles. A multiple kill

⁵⁴ Missile Defense Agency. (2005). *A Day in the Life of the BMDS* (3rd Ed), p. 25.

⁵⁵ *Ibid.*, p. 27.

⁵⁶ From *Program Images* Retrieved February 27, 2007 from <http://www.mda.mil/mdalink/html/nmdimg.html#fm6.ANC>.

vehicle is a carrier vehicle that boosts several kill vehicles into orbit in order to engage threat missiles in the midcourse phase of flight. Each kill vehicle is independently targeted and the carrier vehicle has the ability to assign targets to kill vehicles in flight. It is intended that multiple kill vehicles will be compatible with the ground-based midcourse defense boosters and potentially the Standard Missile-3. Multiple kill vehicles rely on the Ballistic Missile Defense System for target track data.⁵⁷

9. Patriot Advanced Capability-3

The Patriot Advanced Capability-3 missile system is a terminal defense weapon that provides a regional defense against ballistic missiles in the terminal phase of flight. The Patriot system has been successfully employed in operations in the Middle East. Patriot will be used to defend mobile and forward deployed forces. It relies on the Ballistic Missile Defense System for threat detection, but is able to track threat missiles that are in range of its radars.⁵⁸

10. Kinetic Energy Interceptors

Although not yet developed, the purpose of the kinetic energy interceptor program is to develop next generation, kinetic energy kill vehicles that can engage threat ballistic missiles in the boost and midcourse phases of flight. Kinetic energy interceptors will be both land and sea-based and will integrate with current and future delivery platforms.⁵⁹

E. SYSTEM EVOLUTION

The Missile Defense Agency has employed an evolutionary acquisition model in the development of the Ballistic Missile Defense System. After the initial acquisition of core components, block upgrades are performed on a two year cycle. Each block has a specific scope for upgrading the Ballistic Missile Defense System capability.⁶⁰ The scope, functions and hazards of the Ballistic Missile Defense System, as a system of systems, will change over time. Any hazard

⁵⁷ Missile Defense Agency. (2005). *A Day in the Life of the BMDS* (3rd Ed), p. 29.

⁵⁸ *Ibid.*, p. 31.

⁵⁹ *Ibid.*, p. 33.

⁶⁰ *Ibid.*, p. 9.

analysis technique must be capable of keeping pace with the evolution of the system of systems and provide an economical method for updating the safety assessment.

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APPENDIX D. BALLISTIC MISSILE DEFENSE SYSTEM CASE STUDY DATA

The following tables contain attribute values developed by the author. The values do not necessarily correspond to those values assigned by the Missile Defense Agency.

System	Mishap	Consequence
Aegis Destroyer	Radiation causes harm to personnel	Critical
	Radiation causes harm to property	Critical
	Missile exhaust causes harm to personnel	Critical
	Missile impacts friendly system	Catastrophic
	Missile impacts friendly building	Catastrophic
	Missile impacts friendly terrain	Marginal
	Missile impacts hostile terrain	Negligible ⁶¹
Airborne Laser	Laser destroys friendly system	Catastrophic
	Laser radiates friendly system	Critical
	Laser radiates friendly building	Critical
Forward-based X-Band Radar	Radiation causes harm to personnel	Critical
	Radiation causes harm to property	Critical

⁶¹ This is not just an operational mishap. Damage to hostile property and personnel fall within the purview of operational hazards, however, the impact could also cause environmental damage and hence must be considered a system safety mishap.

System	Mishap	Consequence
Ground-based Midcourse Interceptors	Missile exhaust causes harm to personnel	Critical
	Missile impacts friendly system	Catastrophic
	Missile impacts friendly building	Catastrophic
	Missile impacts friendly terrain	Marginal
	Missile impacts hostile terrain	Negligible
Kinetic Energy Interceptor	Missile exhaust causes harm to personnel	Critical
	Missile impacts friendly system	Catastrophic
	Missile impacts friendly building	Catastrophic
	Missile impacts friendly terrain	Negligible
	Missile impacts hostile terrain	Negligible
Multiple Kill Vehicles	Missile exhaust causes harm to personnel	Critical
Patriot Advanced Capability-3	Missile exhaust causes harm to personnel	Critical
	Missile impacts friendly system	Catastrophic
	Missile impacts friendly building	Catastrophic
	Missile impacts friendly terrain	Marginal
	Missile impacts hostile terrain	Negligible

System	Mishap	Consequence
Sea-based X-Band Radar	Radiation causes harm to personnel	Critical
	Radiation causes harm to property	Critical
Terminal High Altitude Area Defense	Missile exhaust causes harm to personnel	Critical
	Missile impacts friendly system	Catastrophic
	Missile impacts friendly building	Catastrophic
	Missile impacts friendly terrain	Marginal
	Missile impacts hostile terrain	Negligible

Table 25. Ballistic Missile Defense System Component System Mishaps

System	Input
Aegis Destroyer	Network Command Cue
	Network Command Fire
	Network Data Target Track
	Network Data Target Type
	Voice Command Fire
Airborne Laser	Network Command Fire
	Network Data Target Track
	Network Data Target Type
	Voice Command Fire
Command and Control Center	Network Data System Location
	Network Data System Status
	Network Data Target Detected
	Network Data Target Track
	Network Data Target Type
	Voice Data Target Detected
Forward-based X-Band Radar	Network Command Cue
	Network Data Target Track
	Network Data Target Type
Ground-based Midcourse Interceptor	Network Command Fire
	Network Data Target Track
	Network Data Target Type

System	Input
	Voice Command Fire
Kinetic Energy Interceptors	Network Command Fire
	Network Data Target Track
	Network Data Target Type
	Voice Command Fire
Multiple Kill Vehicles	Network Command Fire
	Network Data Target Track
	Network Data Target Type
	Voice Command Fire
Patriot Advanced Capability-3	Network Command Fire
	Network Data Target Track
	Network Data Target Type
	Voice Command Fire
Sea-based X-Band Radar	Network Command Cue
	Network Data Target Track
	Network Data Target Type
Space-based Sensors	Network Command Cue
	Network Data Target Track
	Network Data Target Type

System	Input
Terminal High Altitude Area Defense	Network Command Fire
	Network Data Target Track
	Network Data Target Type
	Voice Command Fire

Table 26. Ballistic Missile Defense System Component System Inputs

System	Output
Aegis Destroyer	Network Command Cue
	Network Data System Location
	Network Data System Status
	Network Data Target Detected
	Network Data Target Track
	Network Data Target Type
	Voice Data Target Detected
Airborne Laser	Network Command Cue
	Network Data System Location
	Network Data System Status
	Network Data Target Detected
	Network Data Target Track
	Network Data Target Type
	Voice Data Target Detected

System	Output
Command and Control Center	Network Command Cue
	Network Command Fire
	Network Data Target Detected
	Network Data Target Track
	Network Data Target Type
	Voice Command Fire
Forward-based X-Band Radar	Network Command Cue
	Network Data System Location
	Network Data System Status
	Network Data Target Detected
	Network Data Target Track
	Network Data Target Type
	Voice Data Target Detected
Ground-based Midcourse Interceptors	Network Data System Location
	Network Data System Status
Kinetic Energy Interceptors	Network Data System Location
	Network Data System Status
Multiple Kill Vehicles	Network Data System Location
	Network Data System Status
Patriot Advanced Capability-3	Network Data System Location
	Network Data System Status

System	Output
Sea-based X-Band Radar	Network Command Cue
	Network Data System Location
	Network Data System Status
	Network Data Target Detected
	Network Data Target Track
	Network Data Target Type
	Voice Data Target Detected
Space-based Sensors	Network Command Cue
	Network Data System Location
	Network Data System Status
	Network Data Target Detected
	Network Data Target Track
	Network Data Target Type
Terminal High Altitude Area Defense	Network Data System Location
	Network Data System Status

Table 27. Ballistic Missile Defense System Component Systems Outputs

Input	Mishap	Probability
Network Command Cue Commission	Radiation Causes Harm to Personnel	Remote
Network Command Cue Commission	Radiation Causes Harm to Property	Remote
Network Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Occasional
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Building	Improbable
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Terrain	Remote
Network Data Target Track Subtle Incorrect	Missile Impacts Hostile Terrain	Probable
Network Data Target Type Subtle Incorrect	Missile Impacts Friendly System	Probable
Voice Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Remote

Table 28. Aegis Destroyer Links from Input to Mishap

Output	Probability
Network Command Cue Commission	Remote
Network Data System Location Subtle Incorrect	Occasional
Network Data System Status Subtle Incorrect	Remote
Network Data Target Detected Commission	Probable
Network Data Target Track Subtle Incorrect	Occasional
Network Data Target Type Subtle Incorrect	Probable
Voice Data Target Detected Commission	Occasional

Table 29. Aegis Destroyer Failed Outputs

Input	Mishap	Probability
Network Data Target Track Subtle Incorrect	Laser radiates friendly system	Remote
Network Data Target Track Subtle Incorrect	Laser radiates friendly building	Remote
Network Data Target Type Subtle Incorrect	Laser destroys friendly system	Probable

Table 30. Airborne Laser Links from Input to Mishap

Output	Probability
Network Command Cue Commission	Remote
Network Data System Location Subtle Incorrect	Occasional
Network Data System Status Subtle Incorrect	Remote
Network Data Target Detected Commission	Remote
Network Data Target Track Subtle Incorrect	Occasional
Network Data Target Type Subtle Incorrect	Remote
Voice Data Target Detected Commission	Improbable

Table 31. Airborne Laser Failed Outputs

Input	Output	Probability
Network Data Target Detected Commission	Network Command Cue Commission	Probable
Network Data Target Detected Commission	Network Command Fire Commission	Occasional
Network Data Target Detected Commission	Voice Command Fire Commission	Remote
Network Data Target Track Subtle Incorrect	Network Data Target Track Subtle Incorrect	Frequent
Network Data Target Type Subtle Incorrect	Network Data Target Type Subtle Incorrect	Probable
Voice Data Target Detected Commission	Network Command Cue Commission	Frequent
Voice Data Target Detected Commission	Network Command Fire Commission	Occasional
Voice Data Target Detected Commission	Voice Command Fire Commission	Occasional

Table 32. Command and Control Center Links from Inputs to Outputs

Input	Mishap	Probability
Network Command Cue Commission	Radiation Causes Harm to Personnel	Remote
Network Command Cue Commission	Radiation Causes Harm to Property	Improbable

Table 33. Forward-based X-Band Radar Links from Input to Mishap

Output	Probability
Network Command Cue Commission	Occasional
Network Data System Location Subtle Incorrect	Improbable

Network Data System Status Subtle Incorrect	Remote
Network Data Target Detected Commission	Remote
Network Data Target Track Subtle Incorrect	Occasional
Network Data Target Type Subtle Incorrect	Occasional
Voice Data Target Detected Commission	Remote

Table 34. Forward-based X-Band Radar Failed Outputs

Input	Mishap	Probability
Network Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Occasional
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Building	Improbable
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Terrain	Improbable
Network Data Target Track Subtle Incorrect	Missile Impacts Hostile Terrain	Improbable
Network Data Target Type Subtle Incorrect	Missile Impacts Friendly System	Probable
Voice Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Occasional

Table 35. Ground-based Midcourse Interceptors Links from Input to Mishap

Input	Mishap	Probability
Network Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Remote
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Building	Remote
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Terrain	Occasional
Network Data Target Track Subtle Incorrect	Missile Impacts Hostile Terrain	Occasional
Network Data Target Type Subtle Incorrect	Missile Impacts Friendly System	Occasional
Voice Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Remote

Table 36. Kinetic Energy Interceptors Links from Input to Mishap

Input	Mishap	Probability
Network Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Improbable
Voice Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Remote

Table 37. Multiple Kill Vehicles Links from Input to Mishap

Input	Mishap	Probability
Network Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Remote
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Building	Occasional
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Terrain	Probable
Network Data Target Track Subtle Incorrect	Missile Impacts Hostile Terrain	Improbable
Network Data Target Type Subtle Incorrect	Missile Impacts Friendly System	Frequent
Voice Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Occasional

Table 38. Patriot Advanced Capability-3 Links from Input to Mishap

Input	Mishap	Probability
Network Command Cue Commission	Radiation Causes Harm to Personnel	Occasional
Network Command Cue Commission	Radiation Causes Harm to Property	Improbable

Table 39. Sea-based X-Band Radar Links from Input to Mishap

Output	Probability
Network Command Cue Commission	Occasional
Network Data System Location Subtle Incorrect	Occasional
Network Data System Status Subtle Incorrect	Remote
Network Data Target Detected Commission	Remote
Network Data Target Track Subtle Incorrect	Probable
Network Data Target Type Subtle Incorrect	Occasional
Voice Data Target Detected Commission	Remote

Table 40. Sea-based X-Band Radar Failed Outputs

Output	Probability
Network Command Cue Commission	Remote
Network Data System Location Subtle Incorrect	Remote
Network Data System Status Subtle Incorrect	Remote
Network Data Target Detected Commission	Occasional
Network Data Target Track Subtle Incorrect	Probable
Network Data Target Type Subtle Incorrect	Occasional

Table 41. Space-based Sensors Failed Outputs

Input	Mishap	Probability
Network Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Occasional
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Building	Occasional
Network Data Target Track Subtle Incorrect	Missile Impacts Friendly Terrain	Probable
Network Data Target Track Subtle Incorrect	Missile Impacts Hostile Terrain	Remote
Network Data Target Type Subtle Incorrect	Missile Impacts Friendly System	Occasional
Voice Command Fire Commission	Missile Exhaust Causes Harm to Personnel	Probable

Table 42. Terminal High Altitude Area Defense Links from Input to Mishap

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