Applying System-Theoretic Accident Model and Processes (STAMP) to Hazard Analysis

APPLYING SYSTEM-THEORETIC ACCIDENT MODEL AND PROCESSES (STAMP) TO HAZARD ANALYSIS

BY

YAO SONG, M.Eng.

A THESIS

SUBMITTED TO THE DEPARTMENT OF COMPUTING & SOFTWARE ENGINEERING

AND THE SCHOOL OF GRADUATE STUDIES

OF MCMASTER UNIVERSITY

IN PARTIAL FULFILMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

Master of Applied Science (2012) McMaster University
(Computing and Software) Hamilton, Ontario, Canada

TITLE:	Applying System-Theoretic Accident Model and Processes (STAMP) to Hazard Analysis
AUTHOR:	Yao Song M.Eng., Southeast University, Nanjing, China
SUPERVISOR:	Dr. Alan Wassyng
NUMBER OF PAGES:	x, 95

Abstract

Although traditional hazard analysis techniques, such as failure modes and effect analysis (FMEA), and fault tree analysis (FTA) have been used for a long time, they are not well-suited to handling modern systems with complex software, human-machine interactions, and decision-making procedures. This is mainly because traditional hazard analysis techniques rely on a direct cause-effect chain and have no unified guidance to lead the hazard analysis. The Systems Theoretic Accident Model and Process (STAMP) is based on systems theory to try to find out as much as possible about the factors involved in a hazard, and with providing clear guidance as to the control structure leading to the hazard.

The Darlington Nuclear Power Generating Station was the first nuclear plant in the world in which the safety shutdown systems are computer controlled. Although FTA and FMEA have already been applied to these shutdown systems, Ontario power generation felt that it is still useful to try recent advances to evaluate whether they can improve on the previous hazard analysis.

This thesis introduces the two most common traditional techniques of hazard analysis, FTA and FMEA, as well as two systemic techniques, STPA (which is a hazard analysis method associated with STAMP), and the Functional Resonance Accident Model (FRAM). The thesis also explains why we chose STPA to apply to the Darlington Shutdown System case, and provides an example of the application as well as an evaluation of its use compared with FMEA and FTA.

Acknowledgements

I would like to express my sincere gratitude and appreciation to my professor Dr. Alan Wassyng for his support and encouragement, invaluable guidance and suggestions during my thesis research. I also want to thank Nancy Leveson. It is her new method for hazard analysis upon which this thesis is dependant.

I would like to thank Dr. Spencer Smith and Dr. Mark Lawford for being on my thesis committee and for their valuable comments on my thesis.

Thanks also to Ontario Power Generation (OPG), for suggesting the topic and permission to use information from previous work performed at OPG. In particular, I want to thank Mike Viola and Greg Moum both from OPG, for the information they provided, for attending my seminar on the topic, and for their comments on my work.

Finally, an infinity of thanks goes to my wife. We knew each other, fell in love and got married during my graduate study at McMaster University. As the most important person to me, she is always there with me, with her love, support, understanding and strength.

Contents

List of Figures

Chapter 1

Introduction

1.1 Motivation

Concern about industrial safety dates back many decades and *safety engineering* as a discipline has a long and valuable history. Safety engineering is an applied science strongly related to systems engineering, in particular *system safety engineering*. An important aspect of safety engineering is to conduct hazard analysis to identify risks, and then specify safety features and procedures to mitigate those risks to acceptable levels before the system is certified. Traditional hazard analysis techniques in safety engineering were developed to find causal dependencies between a hazard on the system level and failures of individual components. However, there are always some scenarios that we cannot predict, that may result in a hazard. This situation may even be more significant for computer-controlled systems today. One important reason is that software may contain very complex logic to test (Parnas *et al.*, 1990). Computers are often used in safety-critical applications and provide information to an operator upon request or issue commands as a result of an operator's input. Therefore, when analyzing safety issues of the system, all the components whose operation can directly or indirectly affect safety must be considered, and the related hazards must be eliminated or reduced (Leveson, 1995a).

Nuclear power is one of the domains in which a comprehensive hazard analysis is of vital importance, because an accident in this domain can result in a terrible catastrophe. Huge effort has been expended, and continues to be spent on the safety analysis of nuclear power. However, from (Gusterson, 2011), we know that:

> *"We have now had four grave nuclear reactor accidents: Windscale in Britain in 1957; Three Mile Island in the United States in 1979; Chernobyl in the Soviet Union in 1986; and Fukushima in Japan in 2011."*

Although nuclear engineers have learned a lot from each accident as to how to improve nuclear system design so as to diminish the likelihood of that particular accident repeating itself, the fact is that each accident was unique and supposed to be impossible.

The Darlington Nuclear Power Generating Station, which is operated by Ontario Power Generation Inc (OPG), was the first Canadian nuclear plant to use digital computers to implement the safety shutdown systems. The most common two traditional hazard analysis techniques, Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA), were applied to the shutdown system during development of those systems. However, in keeping with a general interest to keep improving techniques for ensuring the safety of nuclear power plants, OPG was interested in looking for any new advances in hazard analysis techniques that may be useful in this regard.

After conducting a survey and comparison, we finally chose a hazard analysis from a new causality model called STAMP (Systems-Theoretic Accident Model and Processes), developed by Nancy G. Leveson. In STAMP, component failure accidents are still included, but the conception of causality is extended to include component interaction accidents. Safety is reformulated as a control problem rather than a reliability problem (Leveson, 2011). The hazard analysis itself is called STPA (*ST*AMP-based *P*rocess *A*nalysis). In addition to STPA, we also looked at the Functional Resonance Accident Model (FRAM). We believe that STPA is more useful in our context, and the reasons for this are presented in the thesis. As far as we are able, we used the Darlington Shutdown Systems (SDS) as a case study to evaluate the use of STPA compared with FMEA and FTA.

1.2 Overview

The remainder of this thesis is organized as follows:

Chapter 2 presents a survey of the two traditional methods of hazard analysis which are most widely used.

Chapter 3 introduces two systemic methodologies of hazard analysis, STAMP and FRAM.

Chapter 4 describes background information of the Darlington SDS and its architecture and decomposition.

Chapter 5 first discusses the reasons why we chose STPA for the case study, and then illustrates how to apply STPA to the case study. It also presents the comparison between the new results based on STPA and the original FMEA results.

Chapter 6 summarizes the conclusions of this thesis and presents suggestions for future work.

Chapter 2

Survey of Traditional Methods for Hazard Analysis

2.1 Introduction

In this thesis, we use the definition of hazard from (U.S.A. Department of Defense, 2000) as follows:

> *"A hazard is defined as a real or potential condition that can result in injury, illness, or death to personnel; damage to or loss of a system, equipment or property; or damage to the environment."*

Hazard analysis is conducted to identify hazards and the related causal factors to mitigate hazards. Traditional methods for hazard analysis describe the hazard as the result of a sequence of discrete events that occur in a particular order (Hollnagel, 2004). This corresponds to the thinking that was initially based on relatively simple cause-effect propagations, as in Heinrichs well-known Domino Model (H.W.Heinrich, 1931).

Traditional methods for hazard analysis have a clear assumption that there are identifiable cause-effect links that propagate the effects of the hazards (Hollnagel, 2004). Most of them have been widely used for many years. The best known of these are Fault Tree Analysis (FTA), Failure Modes and Effects Analysis (FMEA) and Event Tree Analysis. These methods can be classified into two categories: inductive and deductive. Inductive methods constitute reasoning from individual cases to a general conclusion, while deductive methods go from the general to the specific (Misra, 2008). FMEA and Event Tree Analysis belong to the inductive category. FTA belongs to a deductive category. The following section introduces the two most common hazard analysis methods – FTA and FMEA.

2.2 Fault Tree Analysis (FTA)

FTA was developed in 1962 for the U.S. Air Force by Bell Telephone Laboratories for use with the Minuteman missile system. It was later adopted and extensively applied by the Boeing Company. Today, FTA has become one of the most popular techniques for safety analysis, and is used in many domains like nuclear power, chemistry and aerospace. It is used to determine the root causes and probability of occurrence of a specified undesired event (Ericson, 2005).

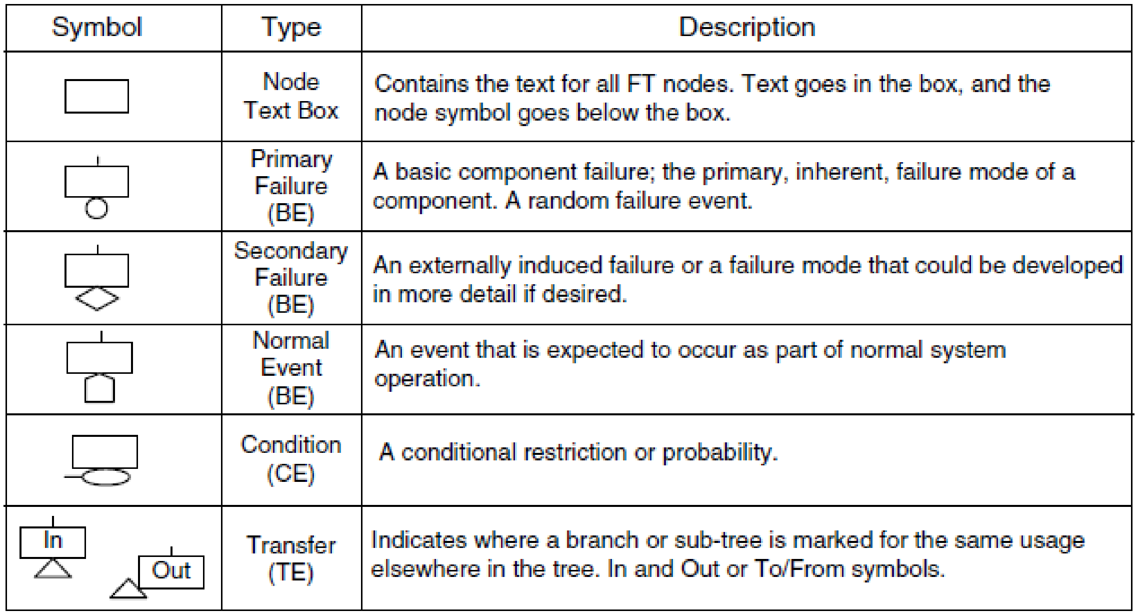
Fault trees provide useful information about the likelihood of a failure occurring and the means by which this failure could occur. They also provide a procedure for determining the various combinations of basic events that can result in the occurrence of a specified undesired event, which is referred to as the top event (Misra, 2008). The basic events represent basic causes for the top event which can be associated with component hardware failures, software failures and human errors. The analysis begins with clearly defining the top event and then determining the various combinations of basic events that can lead to the occurrence of the top event (Ericson, 2005).

Since fault trees provide a compact, graphical, and intuitive method to model the cause-effect relationships, convenient symbols are used to represent the various combinations of events and failure logic that can cause the top event to occur. In the construction of a fault tree, after considering the failure scenario, we attempt to find out what possible causes contribute to it. Once the fault tree is constructed, the probability of occurrence of the top event can be evaluated using analytical or statistical methods.

2.2.1 Basic Concepts

A typical fault tree is composed of a number of symbols interlinked together. The fault tree symbols include primary event symbols, conditioning event symbols, transfer event symbols and gate event symbols. Figure 2.1 introduces the primary, conditioning and transfer event symbols and related descriptions. Figure 2.2 is for gate event symbols and Figure 2.3 for alternative fault tree symbols.
Below are some important definitions of FTA from (Misra, 2008; Ericson, 2005; Stamatelatos and Vesely, 2002):“

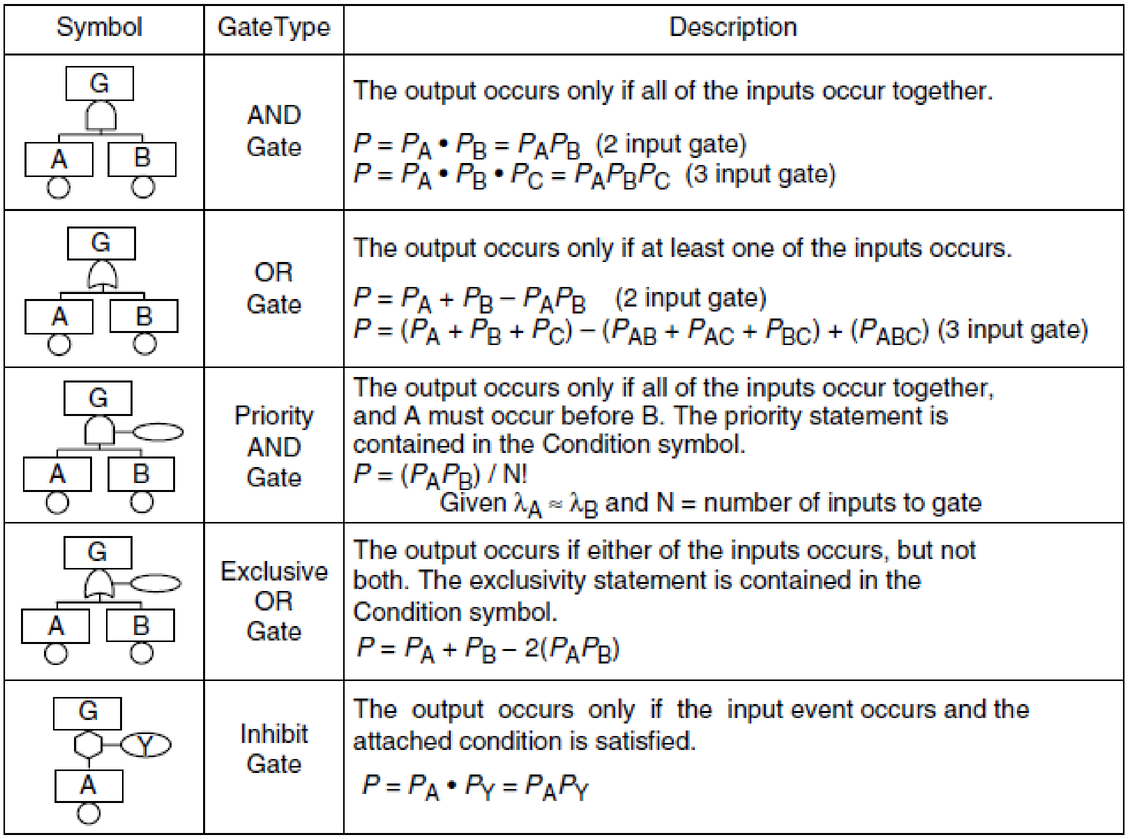
- *Top event: the undesired event in the top level, usually the system failure or accident.*
- *Basic events: represent basic causes for the undesired event. No further development of failure causes is required for basic events.*



Symbol	Type	Description
	Node Text Box	Contains the text for all FT nodes. Text goes in the box, and the node symbol goes below the box.
	Primary Failure (BE)	A basic component failure; the primary, inherent, failure mode of a component. A random failure event.
	Secondary Failure (BE)	An externally induced failure or a failure mode that could be developed in more detail if desired.
	Normal Event (BE)	An event that is expected to occur as part of normal system operation.
	Condition (CE)	A conditional restriction or probability.
In Out	Transfer (TE)	Indicates where a branch or sub-tree is marked for the same usage elsewhere in the tree. In and Out or To/From symbols.

Figure 2.1: Fault tree Symbols for basic events, conditions, and transfers symbols (Ericson, 2005)

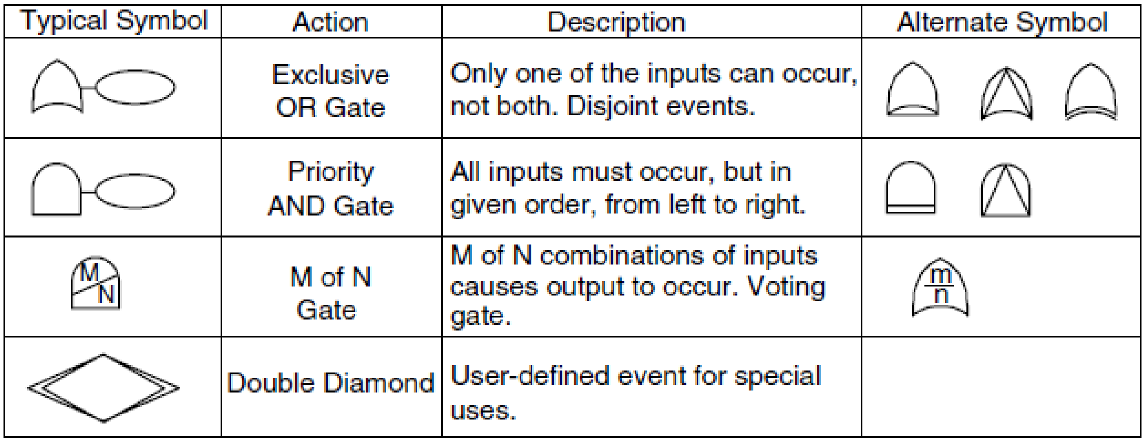
- *Gates: outcomes of one or a combination of basic events or other gates. The gate events are also referred to as intermediate events.*
- *Primary failure: Independent component failure that cannot be further defined at a lower level.*
- *Secondary failure: Independent component failure that is caused by an external force on the system.*
- *Cut set (CS): set of events that together cause the top event to occur. Also referred to as a fault path.*
- *Minimal cut set (MCS): cut set that has been reduced to the minimum number of events that cause the top event to occur. The MCS cannot be further reduced and still guarantee occurrence of the top event.*


G
A
B
G
A
B
G
A
B
G
A
B
G
Y
A

Symbol	GateType	Description
	AND Gate	The output occurs only if all of the inputs occur together. $P = P_A \bullet P_B = P_A P_B$ (2 input gate) $P = P_A \bullet P_B \bullet P_C = P_A P_B P_C$ (3 input gate)
	OR Gate	The output occurs only if at least one of the inputs occurs. $P = P_A + P_B - P_A P_B$ (2 input gate) $P = (P_A + P_B + P_C) - (P_{AB} + P_{AC} + P_{BC}) + (P_{ABC})$ (3 input gate)
	Priority AND Gate	The output occurs only if all of the inputs occur together, and A must occur before B. The priority statement is contained in the Condition symbol. $P = (P_A P_B) / N!$ Given $\lambda_A \approx \lambda_B$ and N = number of inputs to gate
	Exclusive OR Gate	The output occurs if either of the inputs occurs, but not both. The exclusivity statement is contained in the Condition symbol. $P = P_A + P_B - 2(P_A P_B)$
	Inhibit Gate	The output occurs only if the input event occurs and the attached condition is satisfied. $P = P_A \bullet P_Y = P_A P_Y$

Figure 2.2: Fault tree symbols for gate events (Ericson, 2005)

- *Exposure time (ET): length of time a component is effectively exposed to failure during system operation. ET has a large effect on fault tree probability calculations ($P = 1.0 - e^{-\lambda T}$). Exposure time can be controlled by design, repair, circumvention, testing, and monitoring.*
- *Critical path: highest probability CS that drives the top undesired event probability. The most dramatic system improvement is usually made by reducing the probability of this CS."*



Typical Symbol	Action	Description	Alternate Symbol
	Exclusive OR Gate	Only one of the inputs can occur, not both. Disjoint events.	
	Priority AND Gate	All inputs must occur, but in given order, from left to right.	
	M of N Gate	M of N combinations of inputs causes output to occur. Voting gate.	
	Double Diamond	User-defined event for special uses.	

Figure 2.3: Alternative fault tree symbols (Ericson, 2005)

2.2.2 FTA Process and Dynamic FT

FTA Process

The following steps have been suggested for constructing a successful fault tree model: (Misra, 2008; Vesely *et al.*, 1981):

1. Define the undesired event to be analyzed.

2. Define the scope for the analysis.

3. Identify and evaluate fault events which are contributors to the top event. If a fault event represents a primary failure, it is classified as a basic event. If the fault event represents a secondary failure, it is classified as an intermediate event that requires further investigation to identify the prime causes.

4. Complete the gates: all inputs of a particular gate should be completely defined before further analysis of any one of them is undertaken. The fault tree should be developed in levels, and each level should be completed before any

consideration is given to the next level.

Please note that step 3 might be the most important step during the whole FTA process. The essential part of this step is to use a model/method to present the system design and operation. Unfortunately, there is no such a unified method to use. Fault tree construction is usually based on expert knowledge of the system.

Dynamic FT

Fault trees can be classified as static or dynamic trees depending on the sequence relationship between the input events. In static fault trees, the system failure is insensitive to the order of occurrence of component fault events. While in dynamic fault trees, the system failure is sensitive to the order of fault events. Figure 2.4 shows some gate symbols which are usually used in dynamic FTA.

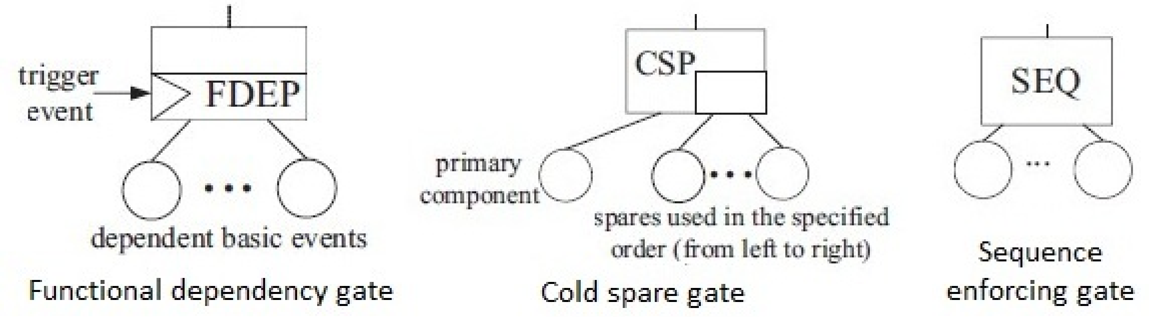


Figure 2.4: Some gate symbols usually used in dynamic FTA (Coppit *et al.*, 2000)

A functional dependency (FDEP) gate has a single trigger input event and one or more dependent basic events. The occurrence of the trigger event forces the dependent basic events to occur. The separate occurrence of any of the dependent basic events has no effect on the trigger event. A cold spare (CSP) gate consists of one primary input event and one or more alternate input events. All the input events are basic events. The primary input represents the component that is initially powered on. The alternate inputs represent components that are initially un-powered and serve as replacements for the primary component. The SEQ gate forces all the input events to occur in a defined order.

2.2.3 Types of Fault Trees Analysis

According to the objectives of the analysis, FTA can be qualitative or quantitative.

Qualitative Analysis

The purpose of qualitative analysis is usually to find minimal cut sets. One of the most common fault tree algorithms for generating CSs is the MOCUS (method of obtaining cut sets) algorithm, developed by J. Fussell and W. Vesely (Fussell and Vesely, 1972).

The algorithm starts at the top gate representing the top event of the fault tree and constructs the set of cut sets by considering the gates at each lower level (Misra, 2008). AND gate means that all the inputs must occur to activate the gate. Thus, the AND gate will be replaced at the lower level by a list of all its inputs. OR gate means that the occurrence of any input can activate the gate. Thus, the cut set being built is split into several cut sets, one containing each input to the OR gate.

Based on minimal cut sets, it is possible to get all the unique combinations of basic events that may result in the top event. Each of them is represented by a minimal cut set. Figure 2.5 provides an example of applying the MOCUS algorithm to an FT. MOCUS can help to identify system hazards that might lead to failure or unsafe states so that proper preventive measures can be taken or reactive measures can be planned.

Quantitative Analysis

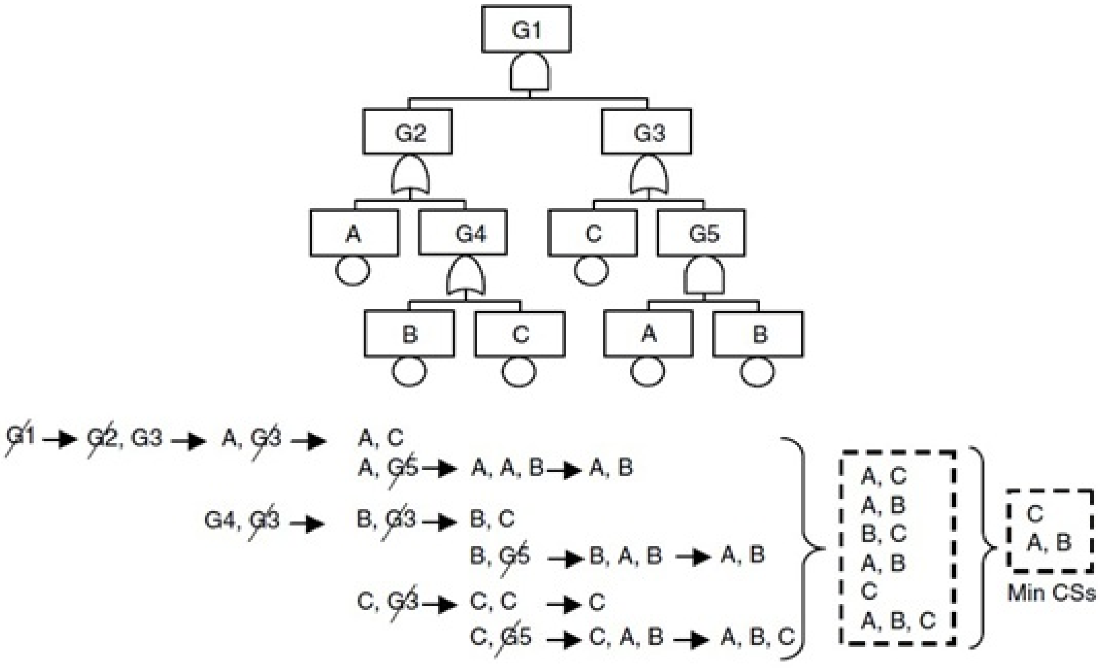


Figure 2.5: MOCUS Example (Ericson, 2005)

Quantitative analysis is based on fault tree mathematics, which includes Boolean algebra, probability theory, and reliability theory. The purpose of quantitative analysis is to determine the probability of the top event occurring, if the probability of each basic event occurring is given. There are three common ways to compute the top fault tree probability: 1) Direct analytical calculation using the fault tree CSs; 2) Bottom-up gate-to-gate calculation; 3) Simulation. Below are some definitions for mathematical terms frequently encountered in FTA from (Ericson, 2005):“

- *Probability of success (R) of a component:* $R = e^{-\lambda T}$, *where* $\lambda =$ *component failure rate and* $T =$ *component exposure time.*

- *Probability of failure (Q) of a component:* $Q = 1 - R = 1 - e^{-\lambda T}$.
- *Boolean rules for FTA. The following Boolean laws apply directly to FTA for the reduction of CS to their minimum components. These rules are required for reducing trees with multiple occurring events (MOEs) in them.*
  $a \times a = a; a + a = a; a + ab = a; a(a + b) = a;$
- *AND gate probability expansion. The probability for an AND gate is:* $P = P_A P_B P_C P_D, ..., P_N$*, where N is equal to the number of inputs to the gate.*
- *OR gate probability expansion. Probability for an OR gate is:*
  $P = (\sum 1^{st} terms) - (\sum 2^{nd} terms) + (\sum 3^{rd} terms) - (\sum 4^{th} terms), ...,$
  $P = (P_A + P_B + P_C) - (P_{AB} + P_{BC} + P_{AC}) + (P_{ABC})$ *(An example for 3-input AND gate.)*
- *Fault tree probability expansion. All of the cut sets ORed together create the Boolean equation for an entire FT. This means that the probability calculation is the OR expansion formula for all of the CS.*
  $CS = CS1; CS2; CS3; CS4; CS5;$
  $P = (\sum 1^{st} terms) - (\sum 2^{nd} terms) + (\sum 3^{rd} terms) - (\sum 4^{th} terms), ...$
  $P = (P_{CS1} + P_{CS2} + ...) - (P_{CS1} \times P_{CS2} + P_{CS2} \times P_{CS3} + ...) + (P_{CS1} \times P_{CS2} \times P_{CS3} + P_{CS1} \times P_{CS2} \times P_{CS4} + ...) - ...$
- *Inclusionexclusion approximation. Most FTs have a large number of CSs. Formulating the exact equation for a large number of cut sets would result in an unwieldy equation, even for a computer. The inclusionexclusion approximation method has been developed to resolve*

this numerical problem. This approximation says that the first term in the OR gate expansion is the upper bound probability for the tree. This means the true probability will be no worse than this value. The first and second terms together compute the lower bound tree probability. This means the true probability will be no better than this value. And, as successive terms are added to the computation, the tree probability approaches the exact calculation. Figure 2.6 shows the OR gate expansion formula along with the terms in the formula for just four CSs. Figure 2.7 shows how, by including each successive term in the calculation, the probability will approach the exact probability."

$$P = \underbrace{P_A + P_B + P_C + P_D}_{\text{1st Term (all singles)}} - \underbrace{(P_{AB} + P_{AC} + P_{AD} + P_{BC} + P_{BD} + P_{CD})}_{\text{2nd Term (all doubles)}} + \underbrace{(P_{ABC} + P_{ABD} + P_{ACD} + P_{BCD})}_{\text{3rd Term (all triples)}} - \underbrace{(P_{ABCD})}_{\text{4th Term (all quads)}}$$

Upper Bound

Lower Bound

Figure 2.6: OR Gate Expansion Formula (Ericson, 2005)

2.2.4 Software Fault Tree Analysis (SFTA)

The FTA principles have been applied to software analysis by Leveson et al. (Leveson *et al.*, 1991; Leveson, 1995b), who introduced templates for the translation of Ada language elements into fault tree building blocks. Also, Software Fault Tree Analysis (SFTA) has been used in real software projects in all relevant development stages – requirements analysis, design and coding (Bowman *et al.*, 2000). It serves as an

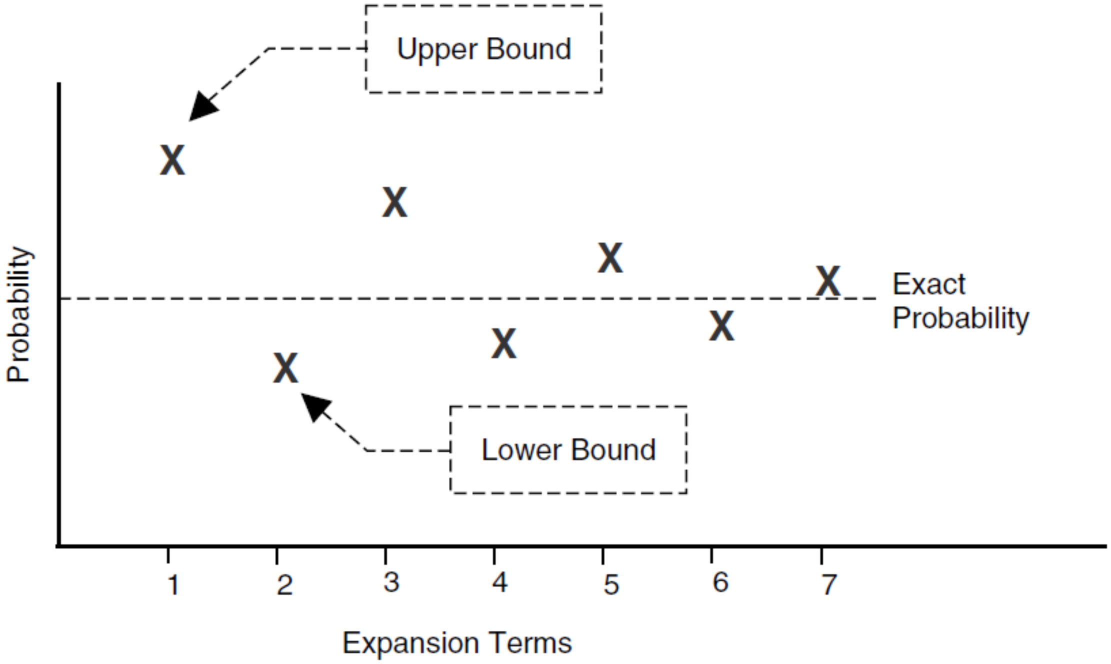


Figure 2.7: First and second terms bound the tree probability (Ericson, 2005)

additional method to gain confidence in the absence of safety critical errors in the software. Tools have been developed to assist fault tree generation from design languages (UML), modelling languages (Matlab/Simulink), or programming languages (Ada) (Weber *et al.*, 2003).

When applied to software, FTA can be used to identify failure modes without regard to probability. In general, software modifications are more readily incorporated than hardware changes, and thus a detailed quantification of the failure probability is not required to justify any software changes that are required to eliminate failure modes and to mitigate the consequences of failures (Bowman *et al.*, 2000).

2.2.5 Summary

FTA is a popular hazard analysis methodology today. It generates a graphic and logic tree structure which allows people to read and understand relatively easily. It can also find root cause for a top event by identifying possible failure causes and their combinations. Additionally, based on logic structure and component failure data, it can provide good quantitative analysis for the probability of the top event.

2.3 Failure Modes and Effects Analysis (FMEA)

2.3.1 Introduction

FMEA is the most commonly used and well known hazard analysis technique to evaluate the potential for failures that can lead to hazards. Its main purpose is to avoid as many potential failures as possible by identifying them and taking appropriate actions in the early stages of design and development (Huang *et al.*, 2000). The FMEA was developed for the U.S. military at first, and mainly used in the aerospace industry (U.S.A. Department of Defense, 1980). During the 1980s, FMEAs were applied to manufacturing and assembly processes by Ford Motor Company (Bertsche, 2008). Today, FMEAs are used in the design of products and processes as well as in the design of software and services in all industries.

FMEA is a disciplined bottom-up evaluation technique. Its fundamental idea is the determination of all possible failure modes for systems, subsystems, or components (Bertsche, 2008). At the same time, the possible failure effects and failure causes are presented. FMEA can provide both qualitative analysis and quantitative analysis. It is a dynamic method which can be used in different development stages (Ericson, 2005).

Another well known version of FMEA is Failure Mode, Effects and Criticality Analysis (FMECA), which enhances the original FMEA by adding criticality evaluation to each failure mode, as well as the evaluation of possible failure mode detection methods.

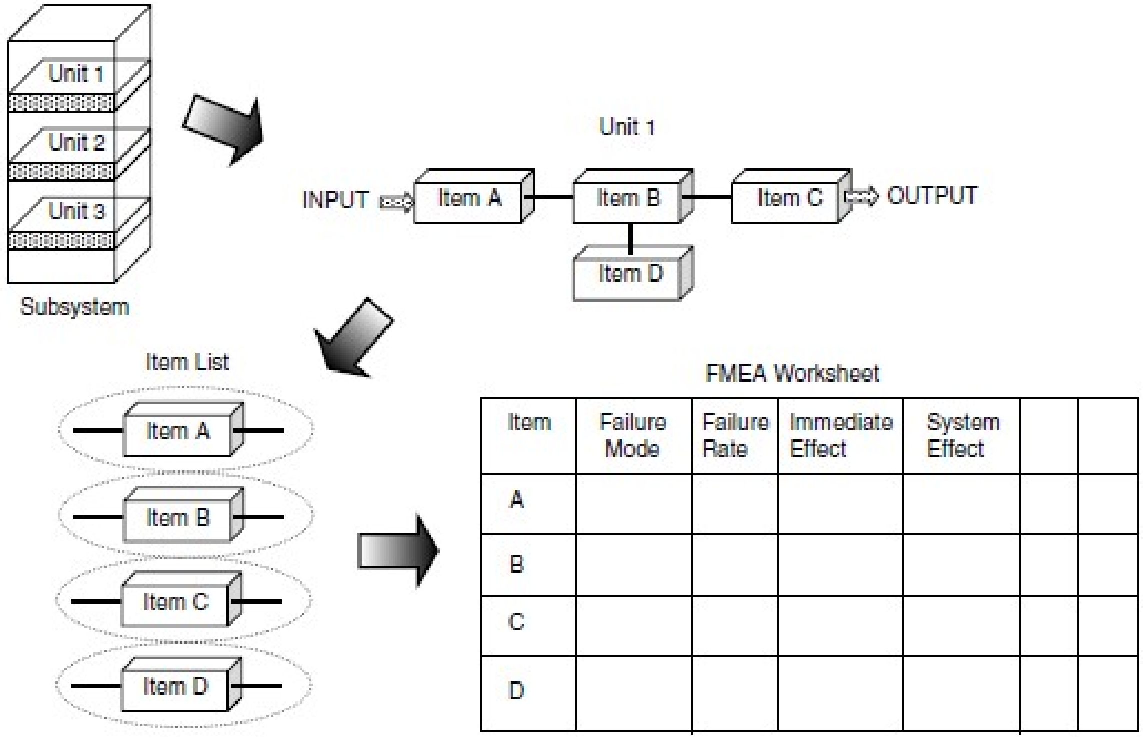
2.3.2 FMEA Basic Concepts and Process

Basic Concepts

Below are some important definitions of FMEA from (Ericson, 2005; U.S.A. Department of Defense, 1980):"

- *Failure: Departure of an item from its required or intended operation, function, or behavior; problems that users encounter. The inability of a system, subsystem, or component to perform its required function.*
- *Failure Mode: The manner by which a failure is observed. Generally describes the way the failure occurs and its impact on equipment operation.*
- *Failure effect: The consequence(s) a failure mode has on the operation, function, or status of an item. It can be divided into immediate effect and system effect.*
- *Failure cause: The physical or chemical processes, design defects, quality defects, part misapplication, or other processes which are the basic reasons for failure or which initiate the physical process by which deterioration proceeds to failure.*

- *Indenture levels: The item levels which identify or describe relative complexity of assembly or function.*
- *Critical item list (CIL): List of items that are considered critical for reliable and/or safe operation of the system.*
- *Risk priority number (RPN): Risk ranking index for reliability.* $RPN =$ *(probability of occurrence)* × *(severity ranking)* × *(detection ranking)." Detection ranking ranks the ability of planned tests and inspections to detect failure modes in time.*



Item	Failure Mode	Failure Rate	Immediate Effect	System Effect		
A						
B						
C						
D						

Figure 2.8: FMEA concept (Ericson, 2005)

Figure 2.8 shows a brief concept of FMEA. The subsystem being analyzed is divided into four units. Each unit is further divided into its basic items. Then each item is listed in the left column of the FMEA worksheet and is individually analyzed.

Process

To conduct an FMEA, it is necessary to understand some system characteristics, such as system functionality, system design and operational constraints. Figure 2.9 depicts an overview of the basic FMEA process. Table 2.1 provides the basic steps in the FMEA process.

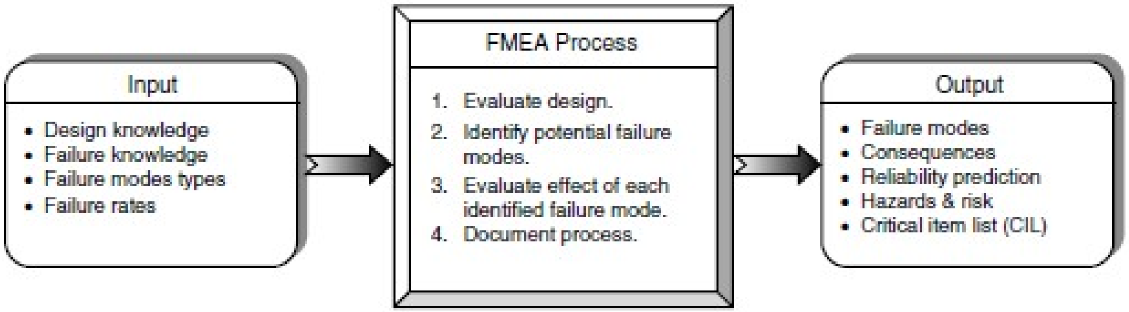


Figure 2.9: FMEA overview (Ericson, 2005)

2.3.3 Types of Analysis Approach and Worksheet Format

Types of Analysis Approaches

There are two primary approaches for accomplishing an FMEA. One is the hardware approach which lists individual hardware items and analyzes their possible failure modes. The other is the functional approach which recognizes that every item is designed to perform a number of functions.

The hardware approach is normally used when hardware items can be uniquely identified from schematics, drawings, and other engineering and design data. It is

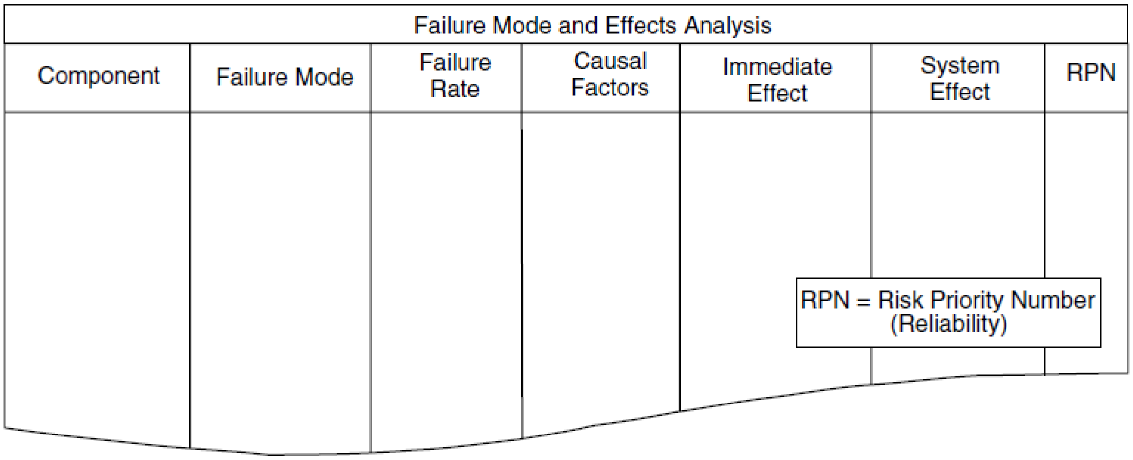
Step	Description
1. Define the system or process to be analyzed.	Create the system definition by dividing the system under analysis into the smallest segments desired for the analysis. Complete system definition includes identification of internal and interface functions, expected performance at all indenture levels, system restraints, and failure definitions.
2. Obtain or construct block diagrams.	Acquire all of the necessary design and process data needed (e.g., functional diagrams, schematics, and drawings) that illustrate the operation, interrelationships, and interdependencies of functional entities involved in the use or operation of the system. Refine the item indenture levels for analysis. Identify realistic failure modes of interest for the analysis and obtain component failure rates.
3. Identify all potential failure modes.	Determine all of the ways in which the items in the system definition can potentially fail.
4. Determine worst-case effects and assign a severity classification.	Begin at the lowest level of the breakdown, evaluate each potential failure mode independently to determine the worst-case effects that may result due to this failure mode on the immediate function or item, on the system, and on the mission. Assign a severity classification to indicate how harmful the effects of this failure mode are on system operation.
5. Identify failure detection methods, corrective actions, and the effects of corrective actions.	For critical failure modes, identify failure detection methods and compensating provisions should the failure mode occur. Determine the design changes that are needed to eliminate a critical failure mode or reduce either the likelihood of its occurrence or impact of its effects. Once steps have been taken to eliminate, reduce, or compensate for a critical failure mode, repeat the analysis until all potential failure modes pose an acceptable level of risk. Once this iterative process is complete, the problems that could not be corrected by design should be documented in a summary.

Table 2.1: FMEA Process (Ericson, 2005; U.S.A. Department of Defense, 1980)

normally used in a bottom-up way. However, it can be initiated at any level of indenture and progress in either direction. The functional approach evaluates system or subsystem based on functions. It is a little more abstract than the hardware approach. The key is to consider each adverse state that is possible for each function. It is normally utilized in a top-down way. However, it can be initiated at any level of indenture and progress in either direction.

Worksheet Format

The FMEA is a detailed analysis of potential failure modes. To provide analysis structure, consistency, and documentation, a form or worksheet is used to perform the FMEA (Ericson, 2005). The specific format of the analysis worksheet is not critical, but a FMEA worksheet usually has the following information: failure mode, failure effects, causal factors and how the failure mode can be detected. Figure 2.10 gives an example of FMEA worksheet for systems safety.



Failure Mode and Effects Analysis

Component	Failure Mode	Failure Rate	Causal Factors	Immediate Effect	System Effect	RPN

RPN = Risk Priority Number (Reliability)

Figure 2.10: An example of FMEA worksheet (Ericson, 2005)

2.3.4 Software Failure Modes and Effects analysis (SFMEA)

The application of FMEA to software is known as SFMEA. Unlike for hardware components, software modules can only display behavior(s) or function(s) of the system. So the analysis approach of SFMEA is functional.

In terms of being used at different levels of system development, SFMEA can be classified into two categories: system-level SFMEA and detailed SFMEA. System-level SFMEAs can be performed early in the software design process, allowing safety assessment of the chosen software architecture. Detailed SFMEAs are applied late in the design process, once at least pseudo code for the software modules is available (Goddard *et al.*, 2000).

According to the way in which functional failure modes are found, SFMEA modes can include: software function fails; function provides incorrect results; software stops or crashes; software exceeds internal capacity; etc.

2.3.5 Summary

FMEA is a widely-used hazard analysis technique. It can provide both qualitative and quantitative analysis on different levels. The focus of the FMEA is on how to consider as many as possible failure modes and failure causes. With a worksheet structure, FMEA is easily understood and relatively inexpensive to perform. FMEA is usually used to perform qualitative hazard analysis.

Chapter 3

Systemic Methods for Hazard Analysis

3.1 Introduction

As described in chapter 2, we know that traditional methods for hazard analysis view hazards as resulting from a chain or sequence of events. The events considered usually involve some type of component failure or human error. Traditional methods use forward sequences (as in FMEA) and/or backward ones (as in FTA) to represent a direct and linear relationship between failure and causality. They maybe work well for losses caused by failures of physical components and for relatively simple systems (Leveson, 2004).

However, there is an indisputable fact that modern systems become more and more complex, which means that more factors no matter whether they be technological, human or organizational, work together in systems. This chapter introduces two hazard analysis methods that are different from those in chapter 2. They are systemic, which means that they treat the system as a whole (either with a control structure or a bundle of process together), to analyze failure and causality of systems. One of them is called System-Theoretic Accident Model and Processes (STAMP). The other is Functional Resonance Accident Model (FRAM).

3.2 System-Theoretic Accident Model and Processes (STAMP)

STAMP was developed by Nancy G. Leveson (Leveson, 2011). It builds on the ideas used in the upper levels of the Rasmussen-Svedung model (Rasmussen and Svedung, 2000), but it continues the control theoretic approach down through and including the technical system and its development and operations. The following table 3.1 lists the foundations of STAMP, which are called new assumptions. For comparison, it also lists the corresponding assumptions of traditional hazard analysis methods, which are called old assumptions.

3.2.1 Basic Concepts for STAMP

STAMP uses three fundamental concepts from system theory: Emergence and hierarchy, Communication and control, and Process models. Detailed instruction for them is described below.

Emergence and Hierarchy

The concept of emergence means that at a given level of complexity, some properties of that level (emergent at that level) are irreducible (Leveson, 2011). Safety is clearly an

Old Assumption	New Assumption
Safety is increased by increasing system or component reliability; if components do not fail, then accidents will not occur.	High reliability is neither necessary nor sufficient for safety.
Accidents are caused by chains of directly related events. We can understand accidents and assess risk by looking at the chains of events leading to the loss.	Accidents are complex processes involving the entire socio-technical system. Traditional event-chain models cannot describe this process adequately.
Probabilistic risk analysis based on event chains is the best way to assess and communicate safety and risk information.	Safety and risk may be best understood and communicated in ways other than probabilistic risk analysis.
Most accidents are caused by operator error. Rewarding safe behaviour and punishing unsafe behaviour will eliminate or reduce accidents significantly.	Operator error is a product of the environment in which it occurs. To reduce operator error we must change the environment in which the operator works.
Highly reliable software is safe.	Highly reliable software is not necessarily safe. Increasing software reliability will have only minimal impact on safety.
Major accidents occur from the chance simultaneous occurrence of random events.	Systems will tend to migrate toward states of higher risk. Such migration is predictable and can be prevented by appropriate system design or detected during operations using leading indicators of increasing risk.
Assigning blame is necessary to learn from and prevent accidents or incidents.	Blame is the enemy of safety. Focus should be on understanding how the system behaviour as a whole contributed to the loss and not on who or what to blame for it.

Table 3.1: Foundations of STAMP From (Leveson, 2011)

emergent property of systems because safety can only be determined in the context of the whole (Leveson, 2011). Statements about safety without the context information are meaningless. Hierarchy theory describes the relationships between different levels, including what generates the levels, what separates them, and what links them.

In STAMP, safety is treated as an emergent property at each of these hierarchy levels that arise when the system components interact within an environment. It depends on the enforcement of constraints on the behavior of the components in the system, including constraints on their potential interactions.

Communication and Control

Control processes mostly operate at the interfaces between two hierarchy levels and always are related with the imposition of constraints. STAMP uses the concept of imposing constraints in system behavior to avoid unsafe events or conditions rather than focusing on avoiding individual component failures.

Between the hierarchical levels of each safety control structure, effective communication channels are needed during the control processes. There are two kinds of communication channels as shown in figure 3.1 (Leveson, 2011). A downward reference channel provides the information necessary to impose safety constraints on the level below. An upward measuring channel provides feedback about how effectively the constraints are being satisfied.

Communication also determines whether the control processes could be established or achieve the expected goals. Typical control processes often use feedback loops to keep interrelated components in a state of dynamic equilibrium. A standard control loop is shown in figure 3.2 (Leveson, 2011).

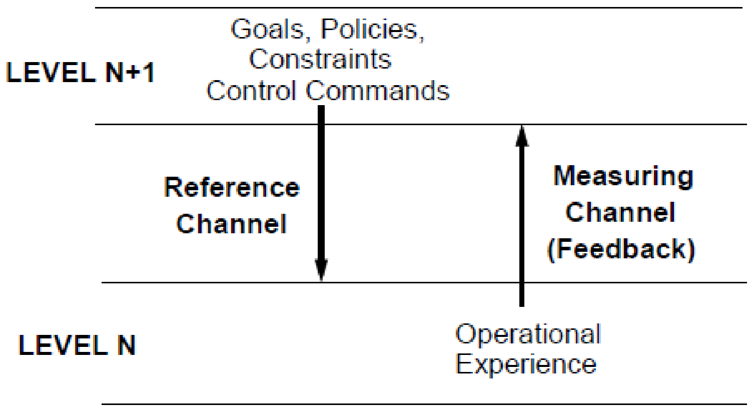


Figure 3.1: Communication Channels between Control Levels (Leveson, 2011)

According to figure 3.2, four conditions are required to establish control processes from (Leveson, 2011; Ashby, 1956):“

- *Goal Condition: The controller must have a goal or goals (for example, to maintain the set point).*
- *Action Condition: The controller must be able to affect the state of the system. In engineering, control actions are implemented by actuators.*
- *Model Condition: The controller must be (or contain) a model of the system. It will be discussed in the following part of process model.*
- *Observability Condition: The controller must be able to ascertain the state of the system. In engineering terminology, observation of the state of the system is provided by sensors. In STAMP, goal condition is the safety constraints that must be enforced by each controller in the hierarchical safety control structure. The action condition is*

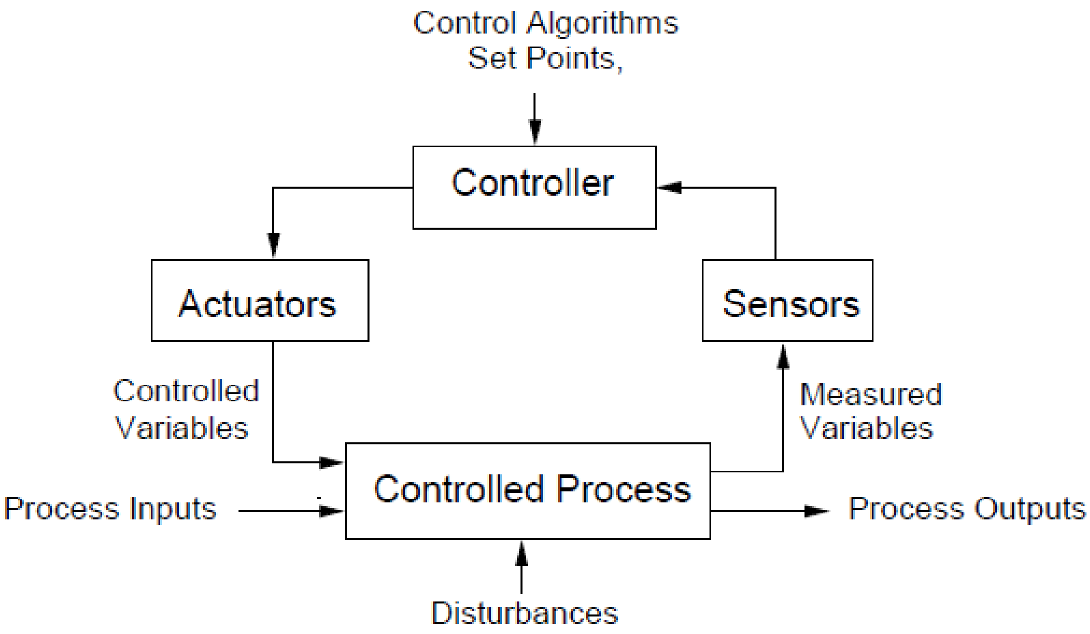


Figure 3.2: A standard control loop (Leveson, 2011)

> *implemented in the downward control channels and the observability condition is embodied in the upward feedback or measuring channels."*

Process Model

Process model is actually a concept in control theory. The reason why it is discussed individually here is just because it is an essential concept of STAMP.

The four conditions required to control a process are already provided above. The most important condition is the model condition. It means that any controller, no matter human or automated, needs a model of the process being controlled to control it effectively. The purpose of using process model is to determine what control actions are needed based on knowing the current state of the controlled process and to estimate the effect of various control actions on that state. For software controller, process model refers to software logic, which can be called logic model. A simple general process model is shown in Figure 3.3.

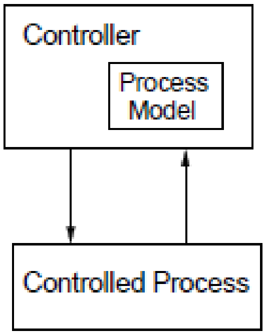


Figure 3.3: A general process model (Leveson, 2011)

The process model could be very simple with only a few variables or very complex with a large number of state variables. If the process model does not match the process, that could result in four different kinds of problems, each of which could lead to an accident. This is especially true for component interaction accidents.

In summary, this systemic approach considers accidents not only arising from component failures, but also from the interactions among system components. It usually does not specify single causal variables for factors (Leplat, 1984). Emergent properties like safety are controlled or enforced by a set of constraints (control laws) related to the behavior of the system components. Safety then can be viewed as a control problem. When control processes provide inadequate control and the safety constraints are violated in the behavior of the lower level processes, accidents occur. In other words, accidents occur when component failures, external disturbances, and/or dysfunctional interactions among system components are not adequately handled by the control system (Leveson, 2011).

3.2.2 Processes for STAMP-Based Process Analysis (STPA)

STPA is a new hazard analysis technique, based on STAMP. It uses a collection of interacting loops of control to analyze systems. It can be used at any stage of the system lifecycle, from before designing to after implementation. The processes of STPA are introduced below (Ishimatsu *et al.*, 2010).

Define System Hazards and Related Safety Constraints

Hazards can be defined in terms of conditions or events, such as loss of equipment or mission. There are no criteria for defining hazards. It depends on subjective evaluation by domain experts (Leveson, 2011). After system hazards are defined, the related safety constraints should be specified by translating the hazards to prevent the hazards.

For example, a hazard and the related safety constraint in an automated elevator door controller from (Leveson, 2011) are described as follows:

> *“ Hazard: A person is present in the doorway when the door is closing.*
>
> *Safety Constraint: An elevator door must not close while anyone is in the doorway.”*

Develop Safety Control Structure

Once the hazards and related safety constraints have been defined, a typical socio-technical hierarchical structure with safety control processes, which is called hierarchical safety control structure, should be described. Figure 3.4 shows a generalized safety control structure diagram, which does not represent any one particular system.

It has two basic parts: system development and system operation. Different hierarchical levels, interactions between these levels, feedback control loops and communication channels can be found in this general form. Each node in the graph is a human or machine component in a socio-technical system. Downward connecting lines show control actions imposed to enforce safety constraints on the system. Upward connecting lines show feedback that provides information to the controllers about how effectively the constraints are being satisfied.

Hierarchical safety control structures can be very complex, so, when analyzing different hazards, only part of the overall structures is considered as the object and the rest is treated as environment factors.

Identify Potentially Inadequate Control Actions

After the safety control structure in system-level has been defined, the next step is to identify the potential for inadequate control, which may drive the system into a hazardous state. A hazardous state is a state that violates the safety constraints that are already defined for the system (H.W.Heinrich, 1931). Below is the identification of inadequate controls from (Leveson, 2011), based on the fact that control actions can be hazardous in four ways:“

1. *A control action required for safety is not provided or is not followed.*
2. *An unsafe control action is provided that leads to a hazard.*
3. *A potentially safe control action is provided too early, too late, or out of sequence.*
4. *A safe control action is stopped too soon (for a continuous or non-discrete control action). Incorrect or unsafe control actions may*

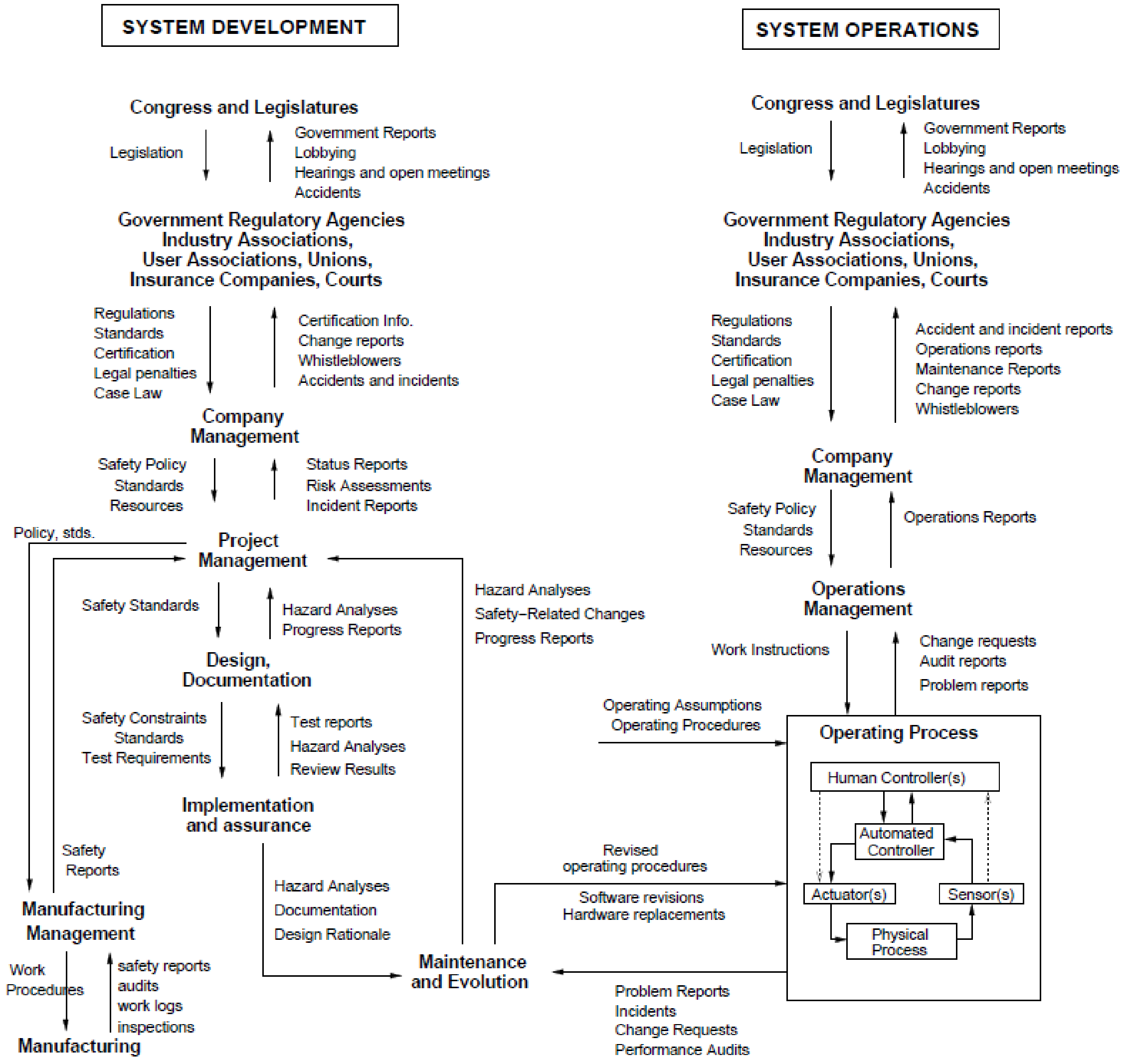


Figure 3.4: General Form of a Model of Socio-Technical Control (Leveson, 2011)

> *cause dysfunctional behavior or interactions among components (Ishimatsu* et al.*, 2010). To ensure a complete assessment, each control action must be investigated in turn."*

Determine How potentially Inadequate Control Actions Could Occur

This step can be performed to identify the scenarios leading to the inadequate control actions that violate the component safety constraints (Leveson, 2011). Once the potential causes have been identified, some methods can be designed and used to prevent or mitigate the identified scenarios. STAMP works on functional control diagrams and is guided by a set of generic control loop flaws (Ishimatsu *et al.*, 2010). Control flaw refers to any imperfection or defect during the control process. Because accidents result from inadequate control and enforcement of safety constraints, the causation of accidents can be understood in terms of control flaws. These control flaws can be classified in three ways. Figure 3.5 shows a classification of control flaws that may lead to hazards. As shown in figure 3.5, there are four types of flaws.

The flaw of type 1 is "control input or external information wrong or missing". Each controller in the hierarchical control structure is itself controlled by higher level controllers. The control action and other information provided by the higher level and required for safe behavior may be missing or wrong. Other types of missing or wrong non-control inputs may also affect the operation of the controller.

The flaw of type 2 is "inadequate control algorithm". Algorithm here refers to the procedures for both hardware controllers and human controllers. It may be inadequate because the algorithm is inadequately designed originally, or the process may change, or the algorithm may be inadequately modified (Leveson, 2011). A human control

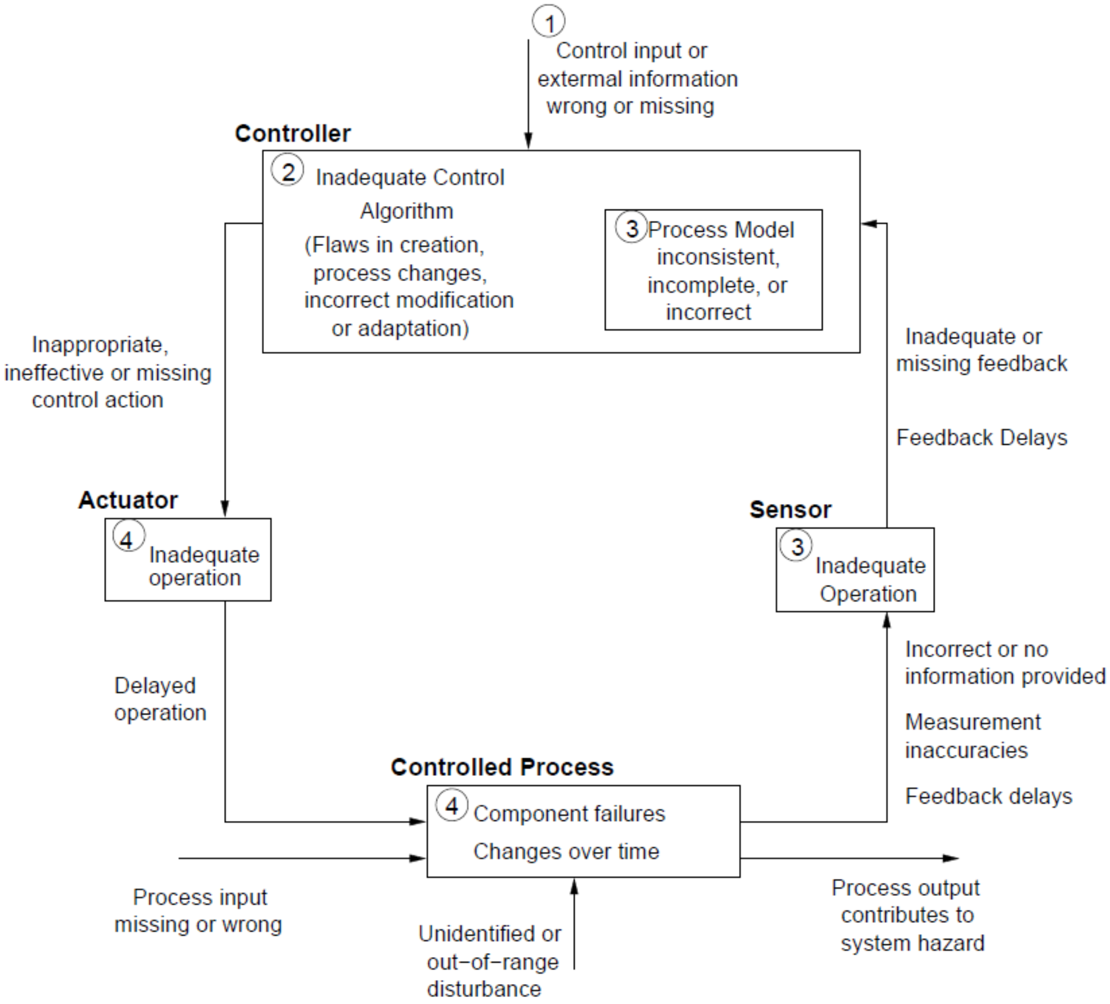

1
Control input or external information wrong or missing
Controller
2 Inadequate Control Algorithm
(Flaws in creation, process changes, incorrect modification or adaptation)
3 Process Model inconsistent, incomplete, or incorrect
Inappropriate, ineffective or missing control action
Inadequate or missing feedback
Feedback Delays
Actuator
4 Inadequate operation
Sensor
3 Inadequate Operation
Delayed operation
Incorrect or no information provided
Measurement inaccuracies
Feedback delays
Controlled Process
4 Component failures
Changes over time
Process input missing or wrong
Unidentified or out–of–range disturbance
Process output contributes to system hazard

Figure 3.5: A classification of control flaws leading hazards (Leveson, 2011)

algorithm is affected by initial training, by the procedures provided to the operators to follow, and by feedback and experimentation over time.

The flaw of type 3 is “process model and sensor”. A process model can be incorrect from the beginning, which means the model is inconsistent with the current process state. A process model may also become incorrect due to feedback missing, delays or measurement inaccuracies.

The flaw of type 4 is “actuator and controlled process”. Even if we assume that the control commands maintain the safety constraints, the control still can be inadequate because the controlled process may not implement theses commands. The reason could be transmission channel failure or actuator or controlled object failure, or the safety of the controlled process may depend on inputs from other system components (Leveson, 2011).

Besides the above four types of flaws, if there are multiple controllers, communication flaws among these controllers also should be considered. These same general factors apply at each level of the socio-technical safety control structure, but the interpretations (applications) of the factor at each level may differ (Ishimatsu *et al.*, 2010). Additionally, if a human or organization is involved, it is necessary to evaluate the context and environment. Since contextual and environmental factors are hard to classify, they will not be discussed here.

3.2.3 Summary

STPA is a systemic method used for hazard analysis. It provides a model-safety control structure, to implement the hazard analysis of system. This model considers hazards and causes in a systemic way rather than just based on component failures or failure events. It also provides guidance to analysts in conducting the hazard analysis. Safety engineers are not required to fill in a blank page using personal experience alone.

3.3 Functional Resonance Accident Model (FRAM)

Another systemic method is the Functional Resonance Accident Model (FRAM). The increasing complexity makes the systems become more closely coupled and the interaction and dependency between individual systems increase (Hollnagel, 2004). To express and analyze the coupling connection, a systemic method should be used in the safety engineering. FRAM is such a systemic method. It analyzes hazards from the coupling connection in the system.

3.3.1 Basic Concepts for FRAM

Concept of Resonance

Resonance is a fundamental concept which is well understood in physical, mechanical, electrical and optical domain. In (Hollnagel and Goteman, 2004), resonance is described as "a relatively large selective response of an object or a system that vibrates in step or phase with an externally applied oscillatory or pushing force, whose frequency is equal or very close to the natural undamped frequency of the system". The difference between normal and stochastic resonance is in the nature of the forcing function.

Concept of Stochastic Resonance

Below is the concept of stochastic resonance from (Hollnagel and Goteman, 2004):

> " *Stochastic resonance is a phenomenon in which a non-linear input is superimposed on a periodic modulated signal. Generally, the non-linear*

> *input is called noise, which is something to be avoided. Noise can be understood as a signal that includes almost all frequencies within a given range at equal amplitude. If noise added to another signal – the message, some components of the noise will amplify the message, while other components of the noise will dampen the message. So the message as a whole becomes distorted and it becomes harder to distinguish the signal from the noise. However, at some point, with some particular frequency range, noise may give more amplification than attenuation to the message when the message is so weak as to be normally undetectable. In this case, the message becomes detectable due to resonance with the stochastic noise. Figure 3.6 shows stochastic resonance."*

Concept of Functional Resonance

Complex systems usually are composed of a number of subsystems, which in turn may comprise multiple functions. If a subsystem or a component is considered by itself, this performance variability can be seen as a weak modulated signal, which normally is undetectable. The rest of the system is the environment, which consists of a number of subsystems, for each of which the performance is variable. The aggregated performance variability of this "environment" can be understood as random noise, and it is this random noise that can give rise to resonance – a performance variability that is too high (Hollnagel and Goteman, 2004).

In the systemic accident model, any part of the system variability can be the signal, with the rest being the noise. The noise is not truly stochastic but is determined by the variability of the functions of the system, which means resonance is a consequence

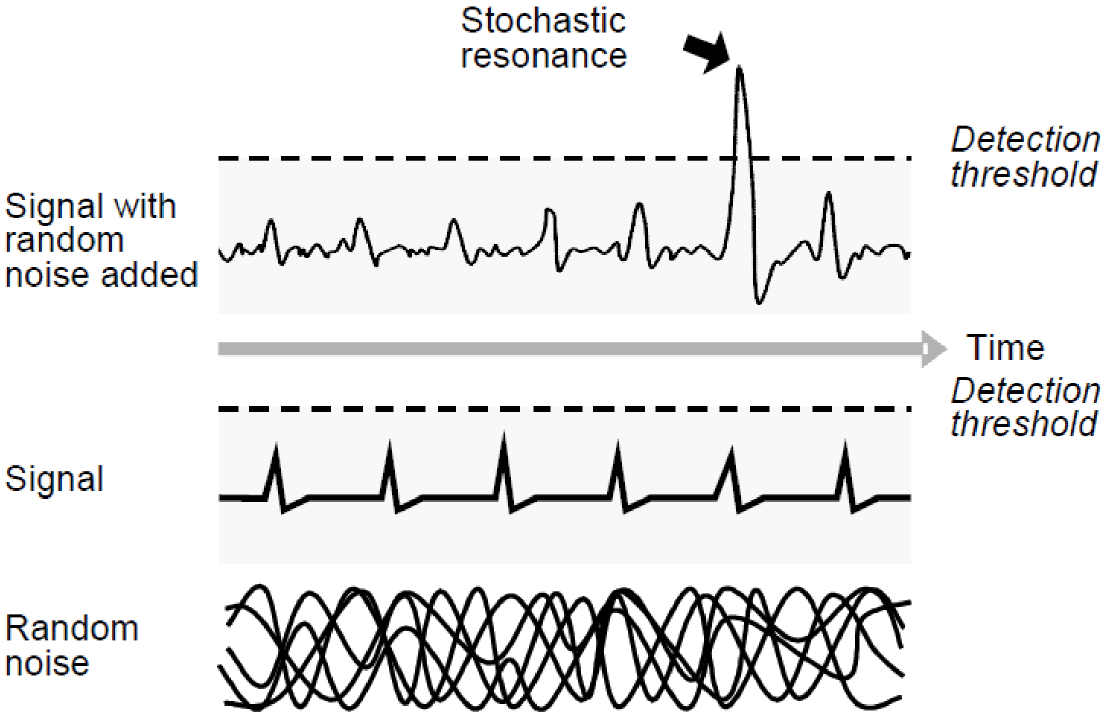


Figure 3.6: Stochastic resonance (Hollnagel, 2004)

of functional couplings in the system. So the name functional resonance makes much more sense than the name stochastic resonance.

3.3.2 Processes for FRAM

Whereas risk analysis normally looks for how individual functions or actions may fail, FRAM focuses on how conditions leading to accidents may emerge. From (Hollnagel, 2004), there are four steps for FRAM in practical terms:

- Identify and characterize essential system functions.
- Characterize the potential for variability.
- Define functional resonance based on identified dependencies among functions.

- Identify barriers for variability (damping factors) and specify required performance monitoring.

Step1: Identify and characterize essential system functions

Functional resonance spread through tight couplings rather than via identifiable and enumerable cause-effect links, so it cannot be described by a simple combination of causal links.

This means FRAM cannot be captured by any of the tree based representations such as fault tree and event tree or by simple graphs such as a Petri net. The reason is that these representations all embody the notion of a sequential development, which is inadequate to show the functional dependencies that are so important to the systemic view (Hollnagel, 2004).

So FRAM use hexagonal graphical representation instead of two dimensions to delineate the functional entities that are of importance for the given scenarios or tasks. A graphical representation of a generic functional entity is shown in Figure 3.7 and the description is introduced below.

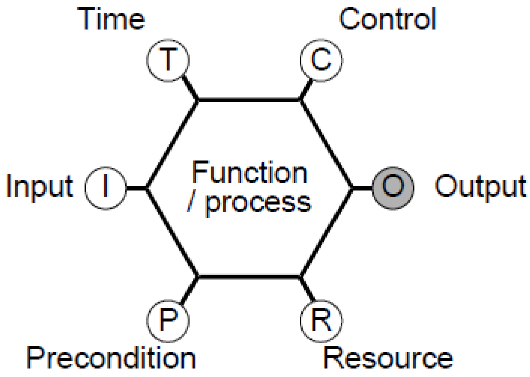


Figure 3.7: The hexagonal function representation (Hollnagel *et al.*, 2008)

- Inputs (I): that which the function processes or transforms or that which starts the function
- Outputs (O): that which is the result of the function, either an entity or a state change.
- Resource (R): that which the function needs or consumes to produce the output.
- Control (C): how the function is monitored or controlled.
- Precondition (P): conditions that must be exist before a function can be executed.
- Time (T): temporal constraints affecting the function (with regard to starting time, finishing time, or duration).

Notice that input, resource, control, precondition and time are often called inputs. And it is useful to be concise in the descriptions, and to use similar terms wherever possible to make matching easier in step 3. Functions can be identified in terms of their purpose or the goals they can bring about. The whole system can be decomposed as a number of functions.

Step 2: Characterize the potential for variability

To figure out how the variability of any function is affected by the variability of the rest of the system, it should characterize the potential for variability of each function at first. The potential for variability depends on the nature of the function in question and on its context. The context is normally considered to be the circumstances in

	How volatile the functions are	How much they depend on the context	Their overall speed or rate of change
Human (M)	High	High	Low
Technological (T)	Low	Low	High
Organizational (O)	Very High	Very High	Very Low

Table 3.2: The comparison of the features of the three categories (Hollnagel, 2004)

which an event occurs or the environment of a system, i.e., that which is outside the boundary (Hollnagel, 2004).

In FRAM, three categories, which are called human (M), technological (T) and organizational (O), are used to classify function. The three main categories of M, T and O have different features with respect to how volatile the functions are, how much they depend on the context, and their overall speed or rate of change. The comparison of the features of the three categories is shown in Table 3.2.

As a conclusion of this, single technological processes typically have a low intrinsic variability, are relatively independent of the context or operating environment, and take place at a high speed. In contrast to that, social and psychological processes have a very high intrinsic variability, depend on the working conditions to a considerable degree, and take place at a slower speed (Hollnagel, 2004).

To assess the potential for variability in more detail, a number of common performance conditions can be used. The relation between each common performance condition and whether it primarily applies to M, T or O functions is introduced in Table 3.3

For the purpose of determining the possibility of functional resonance, each performance condition was rated as (1) stable or variable but adequate; (2) stable or variable

Common Performance Conditions	M T O Functions affected
Availability of resources	M, T
Training and experience	M
Quality of communication	M, T
HMI and operational support	T
Access to procedures and methods	M
Conditions of work	T, O
Number of goals and conflict resolution	M, O
Available time / time pressure	M
Circadian rhythm, stress	M
Crew collaboration quality	M
Quality and support of organization	O

Table 3.3: The relation between common performance conditions and M, T or O functions (Hollnagel, 2004)

but inadequate and (3) unpredictable. Stable or variable but adequate means the associated performance variability is low. Conversely, stable or variable but inadequate means the associated performance variability is high and unpredictable means very high.

Step 3: Define functional resonance based on identified dependencies among functions

This step is to describe the dependencies among functions. To find whether the variability of functions may interact, it requires the functions should be connected directly or indirectly. That means the outputs from one function provide one or more of the inputs (input, preconditions, resources, control, time) to other function(s). So the main purpose of this step is to look for connections that could occur not only under the normal procedure, which are called expected connections, but also certain conditions even though they should not, which are called unexpected connections.

The expected connections can be found simply by looking for matching descriptions of inputs and outputs. This is why it is useful to be concise in the descriptions, and to use similar terms wherever possible (Hollnagel, 2004). If the outputs go outside the system, they need not be considered further. After finding out all the excepted connections, we should pay more attention to the following situations:

- The functions with high performance variability. Especially some of the inadequate or even unpredictable conditions that are common to several functions.
- Special connection structures. Such as the same output goes to more than one other function; several inputs go to one function; and several qualitatively different outputs come from one function.
- Not only first-order connections, but further connections should also be noticed.

Based on the situations above, the next procedure is to find the unexpected connections, by imagining specific conditions under which functional resonance may likely occur. A number of ways of discovering these specific conditions have been useful:

- Consider how specific expected connections may be invalidated or fail, especially for connections involved preconditions;
- Relax the matching requirements. (Usually the requirement is a complete match.)
- Consider artifacts factors which may affect common performance conditions of all the functions.

Step 4: Identify barriers for variability (damping factors) and specify required performance monitoring.

Barriers can be described in terms of barrier systems (the organizational and/or physical structure of the barrier) and barrier functions (the manner by which the barrier achieves its purpose) (Hollnagel and Goteman, 2004). The four fundamental barrier systems are described as follows from (Hollnagel, 2004):"

- *Physical or material barrier systems, that prevent an action from being carried out or an event from taking place or block or mitigate the effects of an unexpected event, such as fences and a physical hindrance for the transportation of mass, energy, or information;*
- *Functional (active or dynamic) barrier systems, that set up one or more pre-conditions that must be met before an action (by human and/or machine) can be carried out, such as air bag of vehicle;*
- *Symbolic barrier systems, that are indications of constraints on action with interpretation needed to achieve their purpose, such as traffic lights;*
- *Incorporeal barrier systems, that lacks material form or substance in the situations where it is applied and instead depends on the knowledge of the user to achieve its purpose, such as rules and guidelines."*

When doing accident or risk analysis, prevention and protection should be considered. That will bring two questions to mind: where barrier functions should be placed in the system and what type of barrier functions should be used? However, there are no simple criteria to answer these two questions. The main approach is based on the type of cause for the potential accident, such as functions with high variability or specific structures of connection. We should also consider other aspects, such as the effectiveness of the barrier function, and costs and delays in implementation.

3.3.3 Summary

FRAM provides a new model (the hexagonal function model) to describe a system as well as a new idea (performance variability) to explain why hazards happen. Like hollnagel said, "FRAM does not endorse the strong assumption that performance conditions directly cause failures or lead to unsafe acts. Instead it simply proposes that the context affects the variability of functions. Even though functional resonance does not provide the final explanation as to why an accident happens, it can serve as a useful analogy to think about accidents and to understand how large effects can accrue, and therefore also ultimately how to prevent them (Hollnagel, 2004)."

Chapter 4

Introduction to the Case Study

We have been working with industry to apply the STPA approach in practice through a project supported by Ontario Power Generation (OPG). This chapter gives a brief introduction to the background of the project, as well as a description of the system architecture and decomposition.

4.1 Project Objectives and Scope

4.1.1 Objectives

This project applies hazard analysis to the Darlington shutdown system, using a systemic method STPA to evaluate whether or not it improves on the original Darlington version of FMEA. The project thus requires a comparison between the new hazard analysis results based on STPA and the previous results.

4.1.2 Scope

There are two totally independent shutdown systems, SDS1 and SDS2, for the Darlington nuclear station, with different programs developed by different teams. Each one uses a different method to shut down the reactors. SDS1 uses cobalt shutoff rods and SDS2 uses liquid poison injection (Bowman *et al.*, 2000). In this thesis, only one shutdown system – SDS1 was analyzed.

We start the hazard analysis on the system-level, and then focus on the trip computer. The document that we have used to understand the system design is the SDS1 *Trip Computer Design Requirements* (TCDR) (Wong *et al.*, 2007). So, when we introduce the system and do the hazard analysis on the system-level, we might omit some detailed information for the other parts of the system. The hazard analysis documents for the Darlington shutdown systems SDS1 and SDS2 are (Yu *et al.*, 2002) and (Guentcheva *et al.*, 2002). STPA can be applied to “system development” and “system operations” stages. In our case, we do not have access to all the system development documents for SDS1, we only applied STPA to the “system operations” stage.

4.2 System Overview

As described above, the Darlington NGS has two independent shutdown systems: SDS1 and SDS2, and we will restrict our attention to SDS1. In SDS1, there are three channels. Each of them is composed of a trip computer, a set of sensors, a set of amplifiers and transmitters, a watchdog, a set of multiplying relays and several logic gates.

The sensors of each channel are used to capture different information from the reactor according to the different responsibilities of the sensors. The information captured by the sensors, which are typically analog signals, is connected to the trip computer by amplifiers and transmitters.

The trip computer in each channel is the core trip logic controller, and replaces the majority of the relay logic used on previous stations. From the trip logic perspective, SDS1 is a three-channel general coincidence logic system, in which a trip of any one or more parameters in a channel can result in a channel trip (Wong *et al.*, 2007). The trip computer is mainly responsible for implementing the trip logic for the channel it belongs to. The trip computer provides other functionalities including: a) channel trip seal-in to ensure that reactor trips, once initiated, go to completion; b) transfer of data to and from the display/test computer; c) calibration of some sensor parameters, and d) self-checks to ensure that internal logic components are working correctly and those external signals are present.

Additionally, each trip computer has an interlock with an external watchdog. The trip computer provides a signal to the watchdog to make it remain active. Otherwise, it will result in a watchdog 'time-out' and thus cause a channel trip. The output from the interlock of trip computer and its external watchdog, will be transmitted to relays through two redundant paths. Each path is connected with two relays. The two out of three voting and the manual trip logic are implemented by using hardware logic to determine whether to shut down the reactor or not. There are also two other computers, the monitor computers and the display/test computers, which interact with the trip computers.

4.3 System Decomposition

The main components and their interactions are described below. Some other components such as amplifiers, transmitters and analogue/digital hardware converters are not described in detail in this thesis.

4.3.1 Trip Computer

Some main features of the trip computer are discussed below:

Trip logic

Each channel has several parameter trips. Each trip parameter has its own trip setpoint. Each sensor signal that exceeds its current setpoint triggers a sensor trip, except for the Heat Transport Low Flow sensor trip which is subject to having to be sustained over a period of time (Wong *et al.*, 2007).

The trip setpoints for some parameters are automatically selected based on reactor power, while others can be set up directly by the human operator. A change in power for trip parameters with power dependent setpoints, may cause the trip setpoint to be switched to a more/less restrictive setpoint depending on the reactor operating conditions and appropriate logic (Wong *et al.*, 2007).

Note that Neutron Overpower (NOP) Gain factors, Channel Power Peaking Factor (CPPF), and High Transport Flow (HTF) Gain factors are provided by the operator. NOP Gain factors are used to calibrate the flux detector signals in the NOP trip. CPPF is used to calculate Estimated Power. HTF Gain factors are used to calibrate HTF signals.

Hysteresis

A deadband (hysteresis) is specified for each trip setpoint. Hysteresis is provided to avoid repeated switching of an output when its associated inputs are close to the trip/conditioning setpoint (Wong *et al.*, 2007). It thus reduces output chatter in the presence of signal noise. Trip region means any signal in this region will result in the corresponding sensor trip. For any signal in a non-trip region, the trip status is untripped. In a hysteresis region, the trip status of any signal inside is not changed. The hysteresis value is a specific constant, defined automatically.

Parameter Trip

Each sensor trip is associated with a parameter trip. There can be more than one sensor trip associated with a single parameter trip, but no sensor trip can be associated with more than one parameter trip (Wong *et al.*, 2007). A sensor trip causes its associated trip parameter to be tripped unless the parameter is conditioned out, or there is a more complex logical dependence of the trip parameter on multiple trip sensor trips.

For all the trip parameters, the logic is such that, when the value is restored to within the non-trip region after a trip has occurred, the parameter trip is automatically cleared. In the case of low neutron power, some trip parameters are required to be inhibited. The status whether a parameter is inhibited or not refers to conditioning status. The inhibition of trip parameters can be done automatically or by the operator.

Channel Trip

If any parameter within the channel is tripped, then the channel is also tripped. Then channel trip status is sealed-in if the channel trip lasts longer than the seal-in time. If it lasts less than the seal-in time, the trip computer does not seal-in the channel trip, which means the channel is cleared automatically if all parameter trips have cleared (untripped). A sealed-in channel trip can be cleared only by the operator, and is permitted only if all parameter trips have cleared.

Performance Timing Requirement

A maximum response time, the performance timing requirement (PTR), is specified for each trip parameter, and is defined to be the total delay from the measured parameter signal input reaching its setpoint, to the time at which the associated parameter trip digital output opens (Wong *et al.*, 2007). Both input and output times are measured from the time at which the inputs and outputs cross the trip computer system boundary.

4.3.2 Watchdog

To ensure that the trip computer is able to take appropriate action when required, the trip computer shall perform a variety of pre-determined self-checks. An important component in the self-check strategy is the watchdog. The watchdog is a special purpose board which must be periodically updated by the trip computer to remain active (Wong *et al.*, 2007). The most probable failure modes of internal logic components will lead to failure to update the watchdog, resulting in a watchdog time-out. A watchdog time-out will lead to a watchdog trip, which will lead to a corresponding channel trip.

4.3.3 Voting Logic sub-system

The voting Logic sub-system is composed of multiple relays, two-out-of-three logic components and OR gates. The channel trip status is passed on to the final two-out-of-three voting logic via two redundant paths. Each path has its own digital output and buffer relays. If a decision is made to trip the channel, the trip computer deenergizes the coils of these buffer relays to open the channel trip contacts in the final voting logic. The OR gate means if any two-out-of-three logic component triggers, the system will be shut down.

4.3.4 Display/Test Computer

Data are transmitted between the display/test computer and the trip computer via two one-way optical links. The trip computer sends the process input and output values and internally generated calculations and status information to the display/test computer. Some of the data are used for the internal functions of the display/test computer, such as display of trip parameter values, setpoints, trip logic status and conditioning status. The communication from the display/test computer to trip computer is called down-link communication. It can be enabled or disabled by the operator.

4.3.5 Monitor Computer

The monitor computer is the interface between the operator and trip computer. All the data transmitted from the trip computer to the display/test computer will finally be shown on the monitor computer. Through the monitor computer, the operator can determine the trip status and the conditioning status of each parameter, the trip status of each channel and each watchdog, and the value of different gain factors such as NOP gain factors, CPPF and HTF gain factors.

4.3.6 Pushbutton and Keyswitch

The pushbutton is a special hardware interface that allows the operator to send commands directly to the trip computer, not through the display/test computer. By using momentary pushbuttons, the operator can condition in/out parameter trips, clear sealed-in channel trip, and enable or disable the down-link communication. The keyswitch is another hardware interface through which the operator can send commands to the display/test computer. By setting up commands using the keyswitch, data can also be transmitted to the trip computer through the display/test computer for the following purposes: 1) to provide new values of NOP flux detector gains, CPPF and HTF gains; 2) to initiate a watchdog test.

4.3.7 Operator

In SDS1, as described above, the operator can send commands to the trip computer either directly by using pushbuttons or the keyswitch. The determination of what commands should be sent is based on the information shown on the monitor computer and logic requirement of the system. Several main responsibilities of operator are described as follows:

- Operator can provide the following three parameters to the trip computer: Neutron Overpower Trip (NOP) Gain factors, Channel Power Peaking Factor (CPPF), and Heat Transport Factor (HTF) gains.

- The operator can condition out some parameter trips at certain power levels.
- The operator can clear a seal-in channel trip if all parameter trips have cleared.
- The operator can enable or disable the down-link communication (from the display/test computer to the trip computer).

Chapter 5

Application of STPA for the Darlington Shutdown System

This chapter presents the application of STPA to hazard analysis of the Darlington Shutdown System. We start from applying STPA to our case, and then compare the new results with the original Darlington FMEA results. Finally, we conclude this chapter with the findings and our concerns revealed during the whole process.

5.1 Why Choose STPA and FMEA for the Darlington Case

As described in chapter 3 and chapter 4, there are several hazard analysis methods, either traditional or systemic. Each method has its own features which may be suitable for a specific project. So when considering which hazard analysis method should be chosen, we should at least analyze the features of the project and the feature of the different methods.

5.1.1 Why Not FTA?

There are two reasons that FTA is not suitable for our case.The most important feature of FTA is that it generates the logic tree structure to represent the logic relationship among the contributory events on different levels. Based on this structure, it is easy for people to read and understand. But it is very difficult to represent all the relationship among all the failure factors, by only using simple symbols such as AND gate, OR gate etc. Especially for hazard analysis in a complex system, not only hardware or software component should be considered, but also environmental factors. For example, when analyzing the hazard "the shutdown system does not shut down the reactor" in our project, not only the hardware and software failure of trip computer should be considered, but also the sensor factor, the operator factor etc. Also, the relationship between them may not be the simple "AND".

The other important feature of FTA is providing quantitative analysis. We can do quantitative analysis in FMEA also but it is secondary. By giving probability values of basic events in a fault tree, FTA provides a method for calculating the probability of the top event. Sometimes, what people want to have is an "accurate" quantitative analysis. But for the hazard analysis of a complex system, if quantitative analysis is needed, there are two problems that cannot be avoided.

The first one is how to get the probability values of basic events. Maybe the probability values of hardware components, if detailed information from the manufacturer is available, are not hard to get. But for software components and human factors, the situation is totally different, because software is a logical construct, instead of a physical entity. It is difficult to make accurate predictions of software reliability and availability. The amount of testing necessary to establish high confidence levels for most software products is impractically large (Parnas *et al.*, 1990).

The second one is high sensitivity. That means the probability of the top event could change significantly even if the probability values of some basic events change only a little. This situation most likely occurs when the fault tree of a complex system becomes very large or a software component is involved in the fault tree. That requires the probability values of basic events in the fault tree to be exactly right; otherwise the calculated probability value of the top event can be meaningless. Obviously, such a requirement is not practical.

5.1.2 Why Not FRAM?

There are several reasons why we think FRAM is not suitable for our case. The key purpose of FRAM is to find out the functional resonance spreading through tight couplings among system functions/procedures. So FRAM is suitable for systems which can be easily divided into multiple functions/procedures. For example, a drug handling system can be divided into the following procedures: registering prescription, fetching the drug from supply, verifying that the correct drug has been fetched, checking preparation and dose, and customer dialogue at hand-over. But for the Darlington shutdown system, there is only one main function/procedure, which is shutting down the reactor.

The second reason is the subjectivity during the process of characterizing the potential for variability. As described in chapter 3, in FRAM, there exists a criterion used to assess the potential for variability. This criterion is composed of a number of common performance conditions. Each condition can be rated as (1) stable or variable but adequate; (2) stable or variable but inadequate and (3) unpredictable. Obviously, in this process human subjective factors play leading role. And there is also no standard to define what range should be counted as high variability. Here, we still use the example of drug handling. In this example, the common performance conditions related with “fetch the drug from supply” include “training and experience”, “available time/time pressure” etc. Obviously, it is hard to have a unified standard to rate these conditions.

The last and the most important reason is that there is no clear way to identify functional resonance based on identified dependencies among functions. To find functional resonance requires that the functions should be connected directly or indirectly. It is easy to identify expected connections, which means the connections occur under the normal conditions. But it is not easy to identify either the unexpected connections or what kinds of connections are prone to cause functional resonance.

In the drug handling example, it is easy to describe all the expected connections as shown in figure 5.1. Then according to the summary of some special connection structures described in chapter 3.3, we may conclude that the connection between “fetch the drug from supply” and “check preparation” is prone to cause functional resonance, because the output of “fetch the drug from supply” feeds into several procedures. But this conclusion seems to represent a random finding, without a clear guide to follow. And in looking for the unexpected connections, we see a similar case.

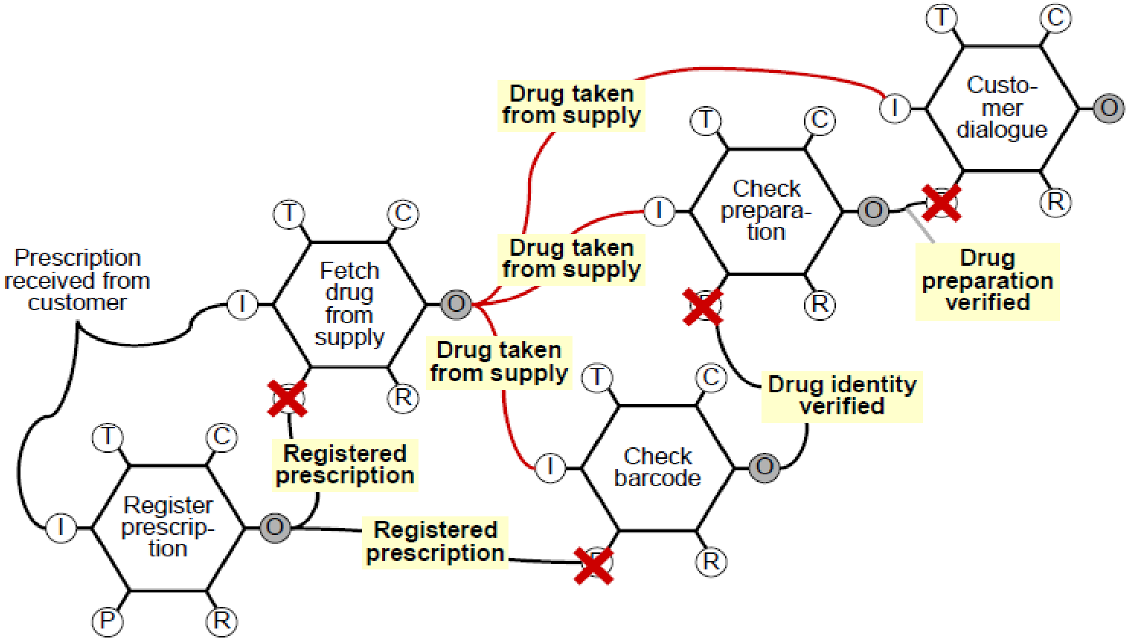


Figure 5.1: FRAM Analysis for Drug Handling Example (Hollnagel, 2004)

5.1.3 Why FMEA and STPA?

Compared with FTA, FMEA is designed to find out as many as possible failure modes as well as the related failure cause and effects, rather than to create a logic model to represent the relationships of the events of system and use mathematical equations to calculate some kinds of values for failures. In many cases, FMEA is used to provide qualitative analysis. Sometimes values like failure rates of components (usually hardware components) would be provided in worksheet, but they are only used to give reference information, not for calculation. FMEA is a bottom-up approach. But it can also be used as a top-down way by developing failure modes from high level to lower level. Additionally, the worksheet format of FMEA is easily understood and performed.

Like all the other traditional methodologies of hazard analysis, FMEA is designed to find the root cause for the hazard identified. However, it is poor at representing systemic accident factors such as structural deficiencies in the organization, management decision-making, and flaws in the safety culture of the company or industry. Besides these, there is also one key limitation for FMEA as well as other methods like FTA and Event Tree Analysis. The limitation is that there is no guidance in identifying hazards and related causal factors.

In FEMA, the failure mode on the highest level could be called a hazard. In FTA, it refers to the top event. The selection of it is arbitrary and usually based on an expert's knowledge of the system. Sometimes it is selected because it represents a type of event that is familiar and thus acceptable as an explanation for the accident or it is a deviation from a standard (Broadbent *et al.*, 1990).

In addition to subjectivity in selecting the events and the root cause event, the links between the events that are chosen to explain them are subjective and subject to bias. In FMEA processes, which are introduced in chapter 2, the steps for identifying all potential failure modes are described as below (Ericson, 2005; U.S.A. Department of Defense, 1980):

> *" Acquire all of the necessary design and process data needed (e.g., functional diagrams, schematics, and drawings) that illustrate the operation, interrelationships, and interdependencies of functional entities involved in the use or operation of the system to build block diagrams. Determine all of the ways in which the items in the system definition can potentially fail."*

From the description above, we can find that there is no guidance to let people know: 1) what kinds of block diagrams are needed; 2) how to build a block diagram;

and 3) how to determine all of the ways in which the items in the system definition can potentially fail. Another point is that identifying all potential failure modes is not realistic, because there is no way to prove completeness.

STPA might make some contributions to these problems. STPA uses a safety control structure to view the hazards and causal factors in the context whole, and does not focus on a specific component in isolation. Another important contribution of STPA is that it provides a systemic way and clear guidance to identify the hazards (corresponding to the failure modes on highest level in FMEA) and the causal factors (corresponding to the failure modes on the lower level and failure causes in FMEA), rather than from an expert's knowledge or imagination. The following section described how to apply STPA to our case.

5.2 How to Apply STPA to Improve FMEA

The hazard analysis for the Darlington case could be classified into three levels. The first phase focuses on the system level, which considers the software, the hardware and all the other environmental factors, to identify the system hazards. The second level focuses on the design of each sub-system/component of the system. The third level of the process is the lowest level, which could be an extension of the design analysis to identify all the detailed failure modes of each component. For software, it could be the source code level.

In this thesis, STPA is applied to the system-level of SDS1. Since there are three independent channels in SDS1, the trip computer and watchdog described below refer to the ones in a single channel.

5.2.1 Define System Hazards and Related Safety Constraints

The first step of STPA is to define the system-level hazards and ensure that appropriate safety constraints are in place. A safety-driven design should start with identifying accidents and then defining the system hazards which would cause these accidents to occur.

The accidents here can be defined as undesired or unplanned events that results in a loss, including loss of human life or human injury, property damage, environmental pollution, mission loss, etc (Leveson, 2011). The hazards here can be defined as system states or a set of conditions that, together with a particular set of hazardous conditions, will lead to an accident (Leveson, 2011). After the system hazards are defined, they should be translated into the corresponding safety constraints, which are restrictions on how the system can achieve its purpose.

For a nuclear power station, obviously the most catastrophic accident is explosion of the nuclear reactor. It can result in releasing large quantities of radioactive contamination into the atmosphere, which can lead to huge loss of human life, property damage, environmental pollution, etc.

So for the Darlington shutdown system, the brief system-level hazard should be: *The reactor fails to trip in the required time if conditions are such that at least 2 channel trips should occur.* The corresponding system safety constraint is that: *The reactor should trip in the required time if conditions are such that at least 2 channel trips should occur.*

For simple systems, this system-level hazard might be enough. While for complex systems, further analysis will be needed to identify the lower level hazards. Section 5.2.3 provides the method of hazard identification.

5.2.2 Develop Safety Control Structure

The second step is to develop the safety control structure for the system. The main work for defining this control structure involves identifying the responsibilities of each component or sub-system as well as all their relationships. It should be in compliance with the System Design Specification. Figure 5.2, below, shows the safety control structure diagram of SDS1 at the system level. It is composed of the following components; Trip Computer, Watchdog, Actuator (Voting Logic sub-system and Rods), Reactor and Sensor (Sensors and Amplifier and transmitter). Please note that there is no standard for control structure. It depends on how much detailed information you want to consider. Here we omit the converters which are used to convert analogue signals to digital signals.

The whole system could be viewed as a control process. Trip computer is the controller, the most important part of the control system. In SDS1, there are three separate trip computers located in three channels. The watchdog could be viewed as a part of controller. It provides a self-check strategy for the trip computer. The actuator is the component executing the action to the object being controlled. In SDS1, there are two separate actuators. Each of them is composed of a number of rods, which execute the action to shut down the reactor. Between the trip computers and actuators, there is a voting logic sub-system, which is composed of multiple relays, two-out-of-three logic components and OR gates. The reactor is the object which is going to be controlled. Sensors will be separately grouped into three channels to capture the status information of the reactor. Different sensors are responsible for capturing different status information of the reactor, such as neutron power, heat transport flow, heat transport pressure, etc. Amplifiers and transmitters are used to

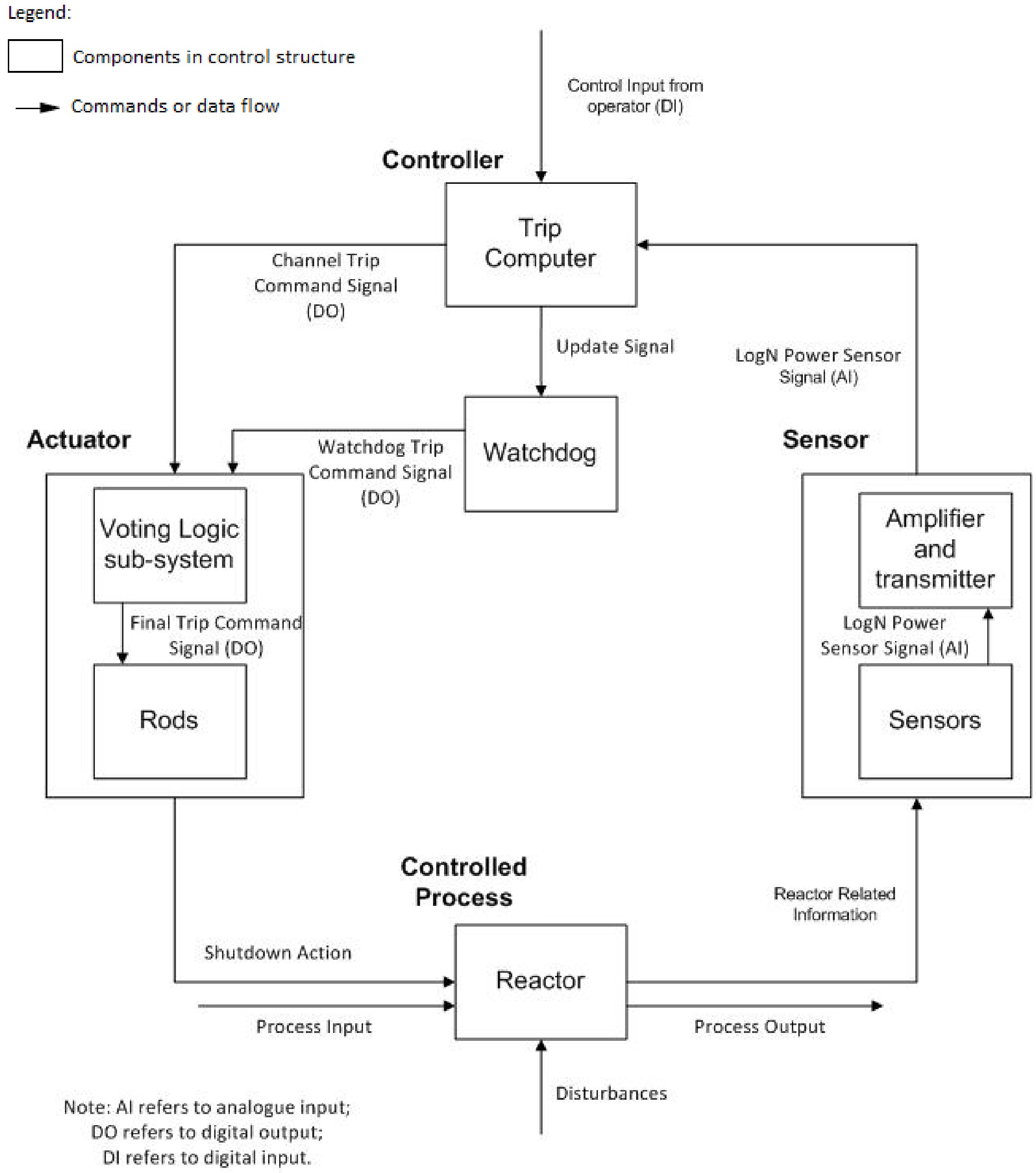

Legend:
Components in control structure
Commands or data flow
Control Input from operator (DI)
Controller
Trip Computer
Channel Trip Command Signal (DO)
Update Signal
LogN Power Sensor Signal (AI)
Actuator
Watchdog
Watchdog Trip Command Signal (DO)
Sensor
Voting Logic sub-system
Final Trip Command Signal (DO)
Rods
Amplifier and transmitter
LogN Power Sensor Signal (AI)
Sensors
Controlled Process
Reactor Related Information
Shutdown Action
Reactor
Process Input
Process Output
Disturbances
Note: AI refers to analogue input;
DO refers to digital output;
DI refers to digital input.

Figure 5.2: Safety Control Structure of SDS1 on System Level

amplify and transmit the analogue signals from sensors. After we understand the role of each component or sub-system as completely as possible, we should add the causal relationship among the components into the diagram.

Some components or sub-systems can have their own safety control structures in a lower level or they play another role in another control structure. For example, the controller – trip computers and voting logic sub-system can be further developed to have their own control structures. This feature demonstrates that STPA can be easily expanded and applied to different levels and will be discussed in section 5.2.4. Figure 5.3 shows the safety control structure of the trip computers of SDS1.

The responsibilities of each component have already been discussed in chapter 4. In figure 5.3, the operator is the controller. The trip computer becomes the controlled object. There are two ways that the operator controls the trip computer. The operator can send commands to the trip computer via a keyswitch and the commands will be transmitted through the display/test computer to the trip computer. This is the indirect way. Another way is that the operator can directly send commands to the trip computer by using a pushbutton. The monitor computer acts as sensors to the operator. It is used to monitor the information of the parameters of the trip computer.

5.2.3 Identify Potentially Inadequate Control Actions

After the system control structure has been defined, the next step is to identify lower level hazards for the system. In section 5.2.1, the system-level hazard has been defined already. For most complex systems, the lower level hazards have to be identified according to the system design specification. STPA views hazards as potentially

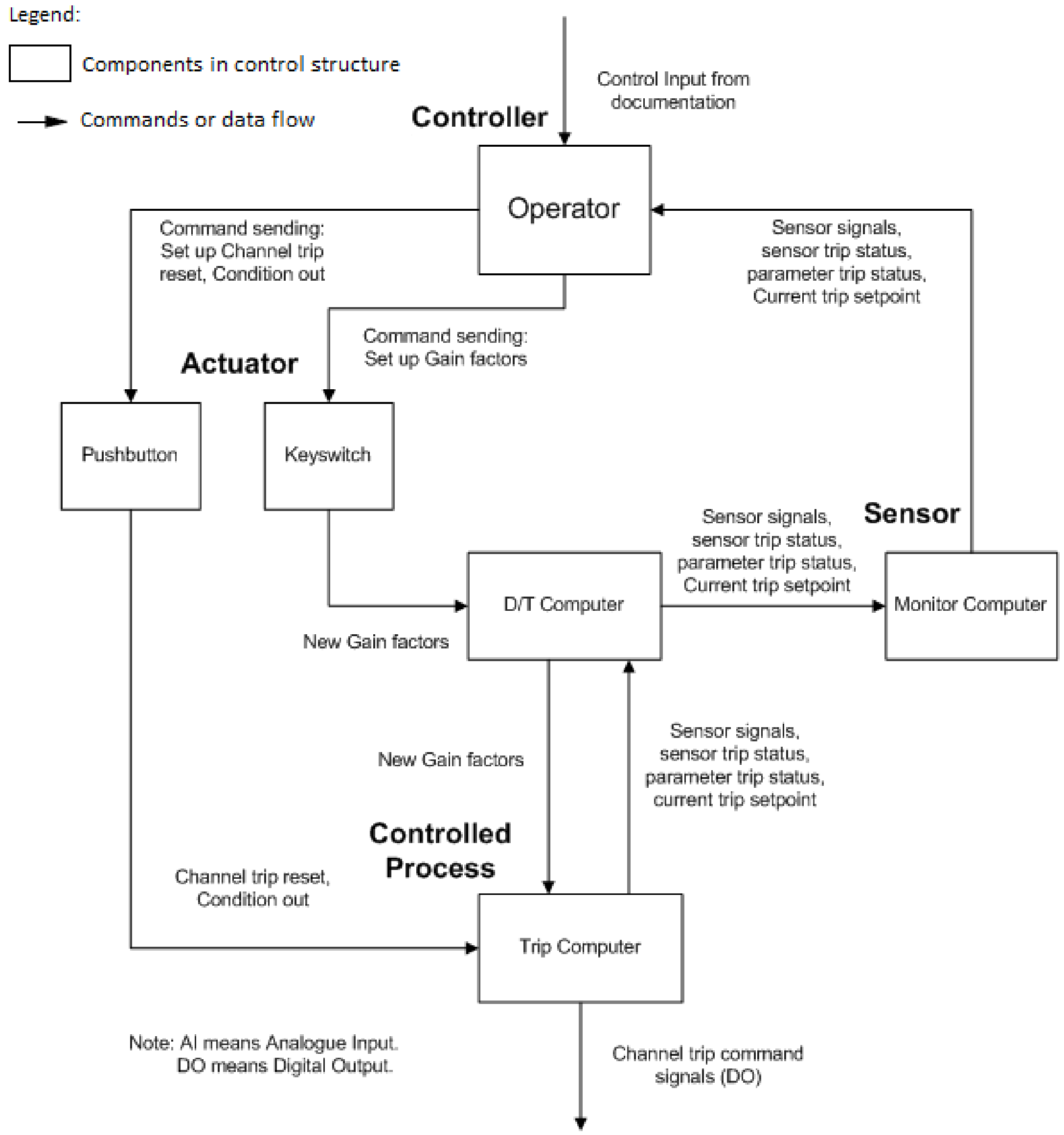

Legend:
Components in control structure
Commands or data flow
Controller
Control Input from documentation
Operator
Command sending: Set up Channel trip reset, Condition out
Sensor signals, sensor trip status, parameter trip status, Current trip setpoint
Command sending: Set up Gain factors
Actuator
Pushbutton
Keyswitch
Sensor signals, sensor trip status, parameter trip status, Current trip setpoint
Sensor
D/T Computer
Monitor Computer
New Gain factors
New Gain factors
Sensor signals, sensor trip status, parameter trip status, current trip setpoint
Controlled Process
Channel trip reset, Condition out
Trip Computer
Note: AI means Analogue Input. DO means Digital Output.
Channel trip command signals (DO)

Figure 5.3: Safety Control Structure of Trip Computers of SDS1

Control Action	From	To	Description
TC_trip on High-LogNPower	Trip Computer	Reactor	Shut down the reactor by trip computer on high LogN power trip condition.
WD_trip on High-LogNPower	Watchdog	Reactor	Shut down the reactor by watchdog.

Table 5.1: Control Actions of High LogN Power Trip

inadequate control actions. So identifying the hazards is actually identifying the potentially inadequate control actions. In the Darlington shutdown system, there are several totally independent parameter trips. Each parameter trip can be viewed as a function of the system. For each function, there are several related control actions. They can be identified according to what kinds of commands the controller can send to controlled process/object related to the selected function. In the Darlington shutdown system, for any parameter trip function in single channel, the trip command that can be sent from the controller to the controlled process is the channel trip command. It can be sent from the trip computer or the watchdog.

In the following sections, we only focus on one parameter trip – High LogN Power Trip to analyze. Because all the parameter trips are separate, the analysis of other parameter trips will be similar. Table 5.1 lists all the related control actions for the High LogN Power Trip function. Both trip computer and related watchdog can send the channel trip command. For each control action, the conditions under which the control action could become inadequate are identified by using the four general categories as follows: (Leveson, 2011)

1. A control action required for safety is not provided or is not followed.

2. An unsafe control action is provided that leads to a hazard.

3. A potentially safe control action is provided too early, too late, or out of sequence.
4. A safe control action is stopped too soon (for a continuous or non-discrete control action).

Table 5.2 shows the potentially inadequate control actions of High LogN Power Trip in the four general categories. Each cell in the table describes what kind of inadequate control action could happen. Each inadequate control action is actually one lower level hazard. Now four system-level hazards (potentially inadequate control actions), marked with a1, a2, b1 and b2, for High LogN Power Trip function are identified.

According to (Yu *et al.*, 2002), in the Darlington shutdown system, hazards can be divided into three classes: Class III, Class II and Class I, with the severity from low to high. Class III system hazards refer to the system hazards which only have a secondary impact in terms of wear and tear on the system as well as economic impact (Yu *et al.*, 2002). Class II system hazards refer to the hazards that the trip logic is reduced to a two-out-of-two system and then redundancy for the trip parameter is reduced. They usually occur when one channel is under testing. Class I system hazards refer to the hazards which have a direct impact to the key functionality of the system. So a1 and b1 belong to Class I; a2 and b2 belong to class III.

5.2.4 Determine How Unsafe Control Actions Could Occur

After hazards have been identified, the following step should identify causal factors, which are very useful to figure out mitigating features against the hazard. Because hazards result from inadequate control and enforcement of safety constraints, the

Control Action	Category 1: A control action required for safety is not provided or is not followed.	Category 2: An unsafe control action is provided that leads to a hazard.	Category 3: A potentially safe control action is provided too early, too late, or out of sequence).	Category 4: A safe control action is stopped too soon.
TC_trip on HighLogN-Power	Trip computer fails to send channel trip command when high LogN power is greater than setpoint. (a1)	If WD_trip on HighLogN-Power was provided instead of "TC_trip on HighLogN-Power", no hazard will occur.	Trip computer sends parameter trip when high LogN power is equal or less than setpoint. (a2)	TC_trip is stopped too soon that the reactor does not get the channel trip signal. (a1)
WD_trip on High-LogN-Power	Watchdog fails to send a watchdog trip when it does meet time-out requirement. (b1)	If TC_trip on HighLogNPower was provided instead of WD_trip on HighLogNPower, no hazard will occur.	Watchdog sends a watchdog trip when it does not meet time-out requirement. (b2)	WD_trip is stopped too soon that the reactor does not get the channel trip signal. (b1)

Table 5.2: Potentially inadequate control actions of High LogN Power Trip

causal factors can be understood in terms of control flaws. Figure 3.5 has already shown a classification of control flaws leading to hazards. The safety control structure diagram is evaluated by using this classification of control flaws. Please note that not all the control flaws will contribute to the hazard, which means not all the control flaws will become the causal factors. It depends on different cases. Here, hazard a1 is selected to be analyzed first. According to figure 3.5 and our system features, we create figure 5.4 to show Causal factors leading to hazard a1.

For convenience, figure 5.5 is used to record and group the causal factors of hazard a1. Please note that the causal factor of "control input (from operator) wrong or missing" needs to be further developed. This is because the trip computer exists in another control loop which is already shown in figure 5.3. In the system-level control structure, the trip computer is the controller. While in the lower level control structure, it becomes the controlled object. Therefore, "control input (from operator) wrong or missing" has to be developed further for the lower level control structure. So the analysis will follow the same processes from 5.2.2 to 5.2.4.

For some cells marked with "to be decided", it means that more detailed information is needed. In our case, the only supporting documentation that we have is (Wong *et al.*, 2007), so the causal factors of other parts in the control loop are marked with "to be decided".

Now, we are going to analyze "control input (from operator) wrong or missing". Since control input is actually the control command sent from the operator, we will start with the function "operator sends commands on high LogN power trip condition". Table 5.3 lists the control actions related to this function. Since High LogN Power trip does not need gain factors from the operator, there are only two control

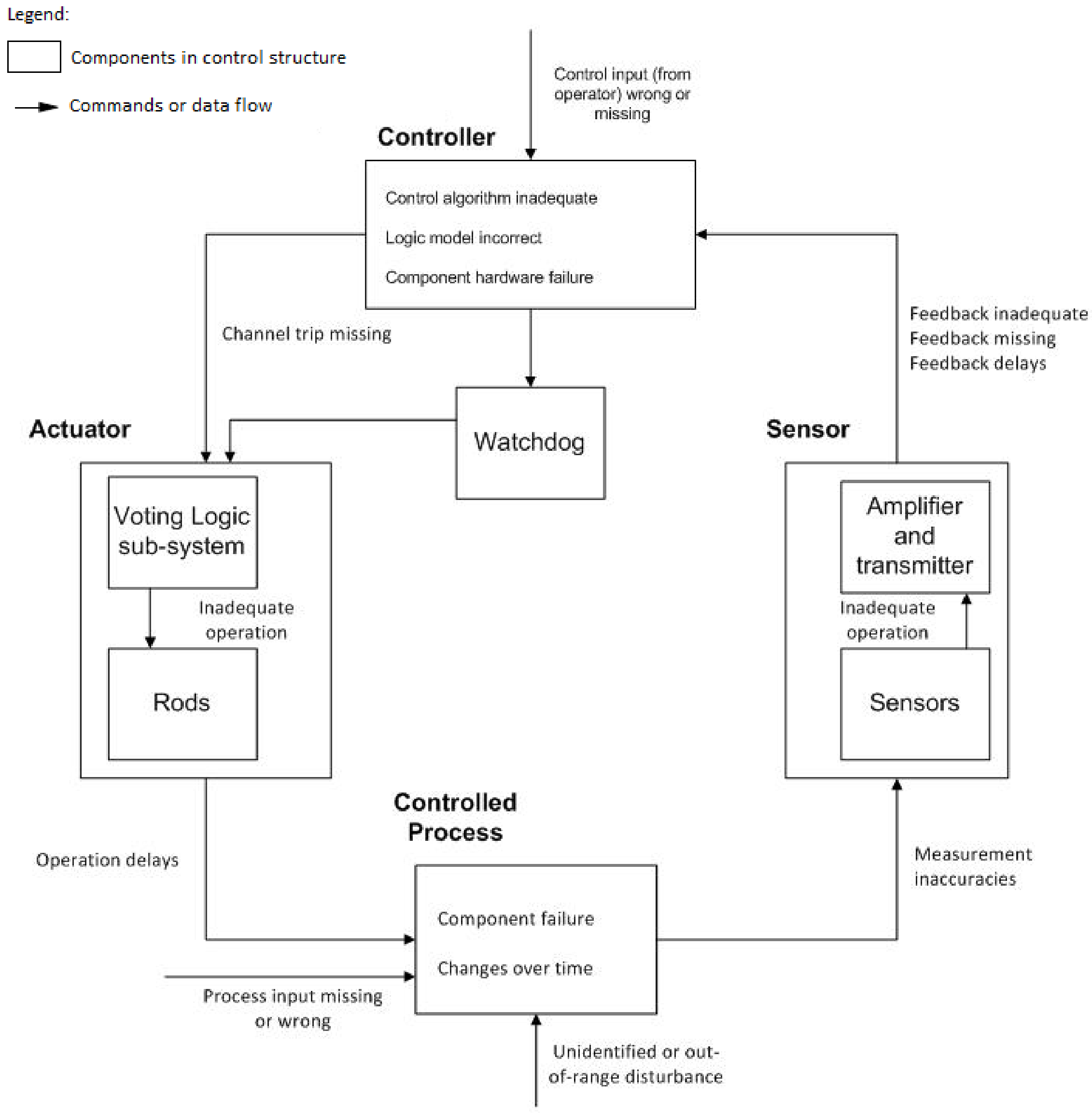
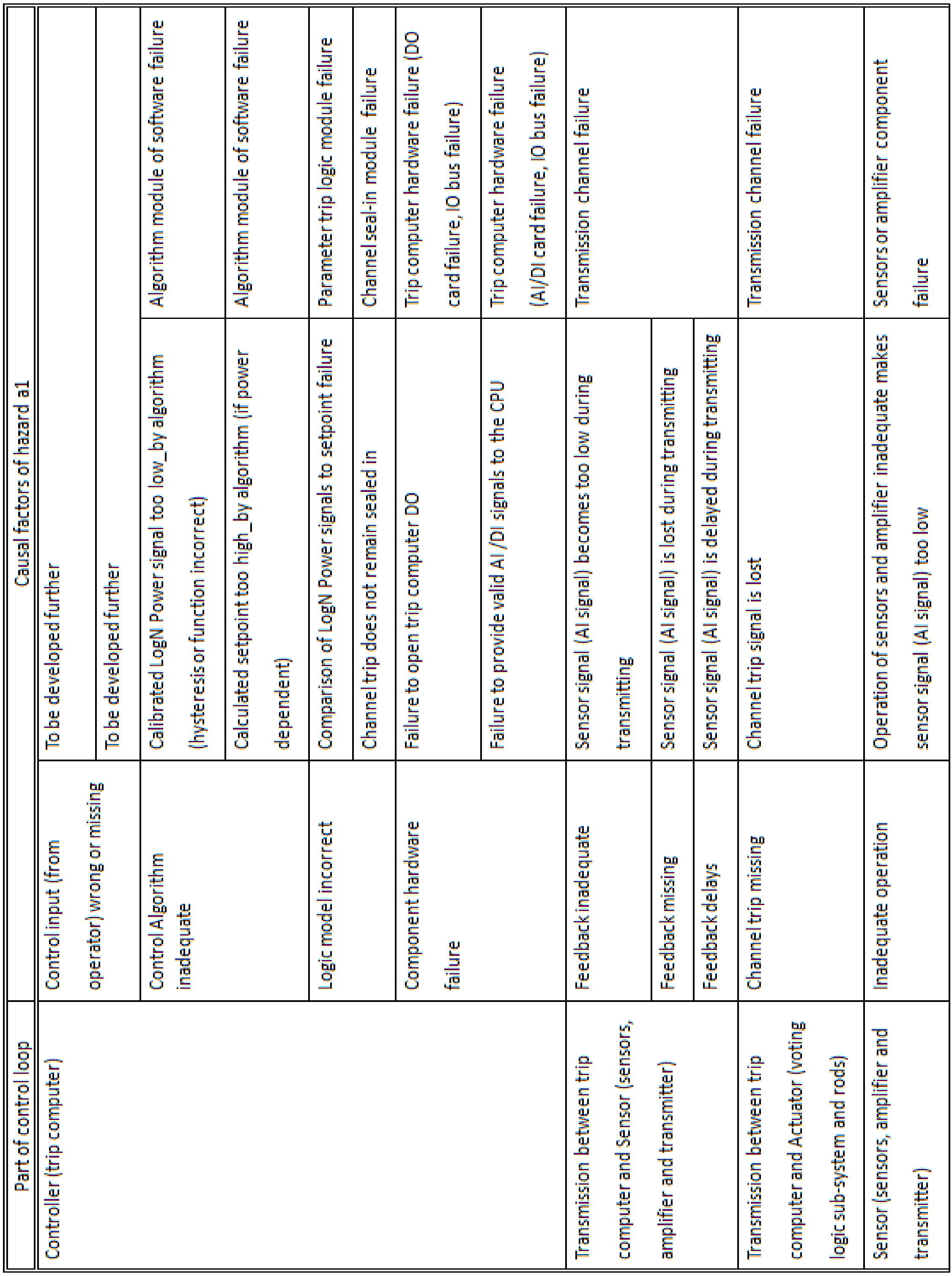
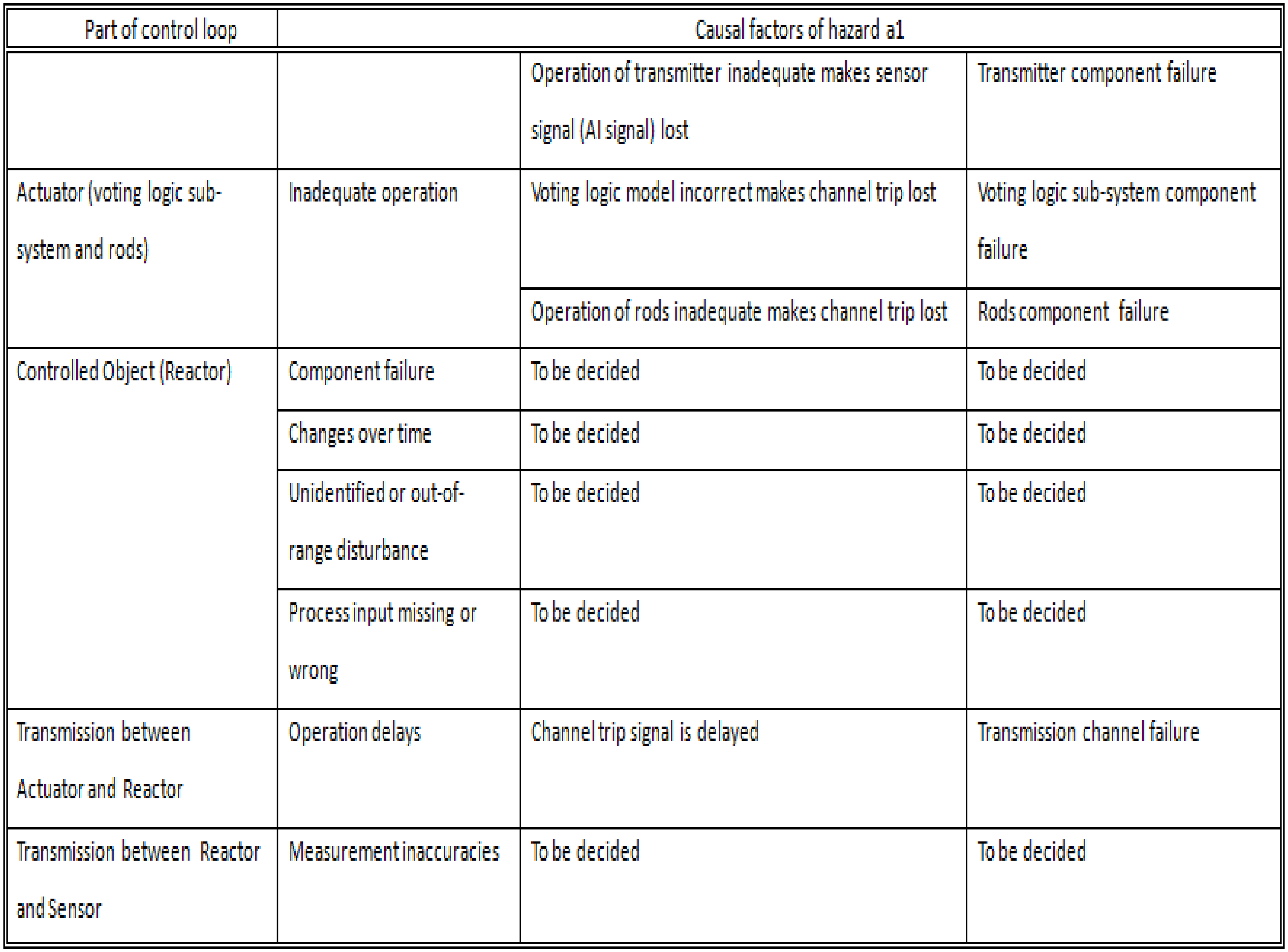


Figure 5.4: Causal factors leading to hazard a1



Part of control loop	Causal factors of hazard a1		
Controller (trip computer)	Control input (from operator) wrong or missing	To be developed further	
		To be developed further	
	Control Algorithm inadequate	Calibrated LogN Power signal too low_by algorithm (hysteresis or function incorrect)	Algorithm module of software failure
		Calculated setpoint too high_by algorithm (if power dependent)	Algorithm module of software failure
	Logic model incorrect	Comparison of LogN Power signals to setpoint failure	Parameter trip logic module failure
		Channel trip does not remain sealed in	Channel seal-in module failure
	Component hardware failure	Failure to open trip computer DO	Trip computer hardware failure (DO card failure, IO bus failure)
		Failure to provide valid AI /DI signals to the CPU	Trip computer hardware failure (AI/DI card failure, IO bus failure)
Transmission between trip computer and Sensor (sensors, amplifier and transmitter)	Feedback inadequate	Sensor signal (AI signal) becomes too low during transmitting	Transmission channel failure
	Feedback missing	Sensor signal (AI signal) is lost during transmitting	
	Feedback delays	Sensor signal (AI signal) is delayed during transmitting	
Transmission between trip computer and Actuator (voting logic sub-system and rods)	Channel trip missing	Channel trip signal is lost	Transmission channel failure
Sensor (sensors, amplifier and transmitter)	Inadequate operation	Operation of sensors and amplifier inadequate makes sensor signal (AI signal) too low	Sensors or amplifier component failure

Figure 5.5: Causal factors of hazard a1



Part of control loop	Causal factors of hazard a1		
		Operation of transmitter inadequate makes sensor signal (AI signal) lost	Transmitter component failure
Actuator (voting logic sub-system and rods)	Inadequate operation	Voting logic model incorrect makes channel trip lost	Voting logic sub-system component failure
		Operation of rods inadequate makes channel trip lost	Rods component failure
Controlled Object (Reactor)	Component failure	To be decided	To be decided
	Changes over time	To be decided	To be decided
	Unidentified or out-of-range disturbance	To be decided	To be decided
	Process input missing or wrong	To be decided	To be decided
Transmission between Actuator and Reactor	Operation delays	Channel trip signal is delayed	Transmission channel failure
Transmission between Reactor and Sensor	Measurement inaccuracies	To be decided	To be decided

Control Action	From	To	Description
Sending condition in/out command	Operator (through pushbutton)	Trip computer	Operator enables/disables the parameter trip.
Sending channel trip reset command	Operator (through keyswitch)	Trip computer	Operator sends channel trip reset to clear channel trip.

Table 5.3: Control Actions of “operator sends command on High LogN Power Trip condition”

actions left.

Table 5.4 identified the potentially inadequate control actions. In table 5.4, three hazards c1, d1 and e1 are identified. The hazard c1 will be chosen to be analyzed to identify the causal factors. Figure 5.6 shows the causal factors of hazard c1. Please note that c1 is quite different with a1, d1 and e1. The hazard c1 refers to incorrect action which should not occur but does occur. The hazards a1, d1 and e1 refer to correct actions which should occur but do not occur. So for c1, inadequate operation for actuator, condition out missing, and operation delays will not lead to the hazard and will not be considered.

Another special point is that when the controller is a human controller, the analysis will be complex. Figure 5.7 shows the relationship between mental models. So when analyzing the operator’s model, including the algorithm model and the logic model of the operator, we should consider operational procedures, training and operational experience.

For convenience, figure 5.8 is used to record and group the causal factors of hazard c1. The analysis of d1 and e1 is similar with a1. Figure 5.9 is for causal factors of d1. Figure 5.10 is for causal factors of e1. Note that actuator for d1 and e1 are different. One is using a pushbutton and the other is using the keyswitch.

Control Action	Category 1: A control action required for safety is not provided or is not followed.	Category 2: An unsafe control action is provided that leads to a hazard.	Category 3: A potentially safe control action is provided too early, too late, or out of sequence).	Category 4: A safe control action is stopped too soon.
Sending condition out command (through pushbutton)	Condition out command sent incorrectly. (c1)	If "Sending condition out command" is not provided, instead of providing any of the other two, no new hazard occurs.	If "Sending condition out command" too early, (c1).	Condition out command is stopped too soon that the trip computer does not receive the signal, no new hazard occurs.
Sending condition in command (through pushbutton)	Fail to send condition in command. (d1)	If "Sending condition in command" is not provided, instead of providing any of the other two, no new hazard occurs.	If "Sending condition in command" too late, (d1).	Condition in command is stopped too soon that the trip computer does not receive the signal. (d1)
Sending channel trip reset command (through keyswitch)	Channel trip reset command sent incorrectly. (e1)	If "Sending channel trip reset command" is not provided, instead of providing any of the other two, no new hazard occurs.	If "Sending channel trip reset command" too early, (e1).	Channel trip reset command is stopped too soon that the channel trip is still sealed-in, no new hazard occurs.

Table 5.4: Potentially Inadequate Control Actions of "operator sends control command" on High LogN Power Trip

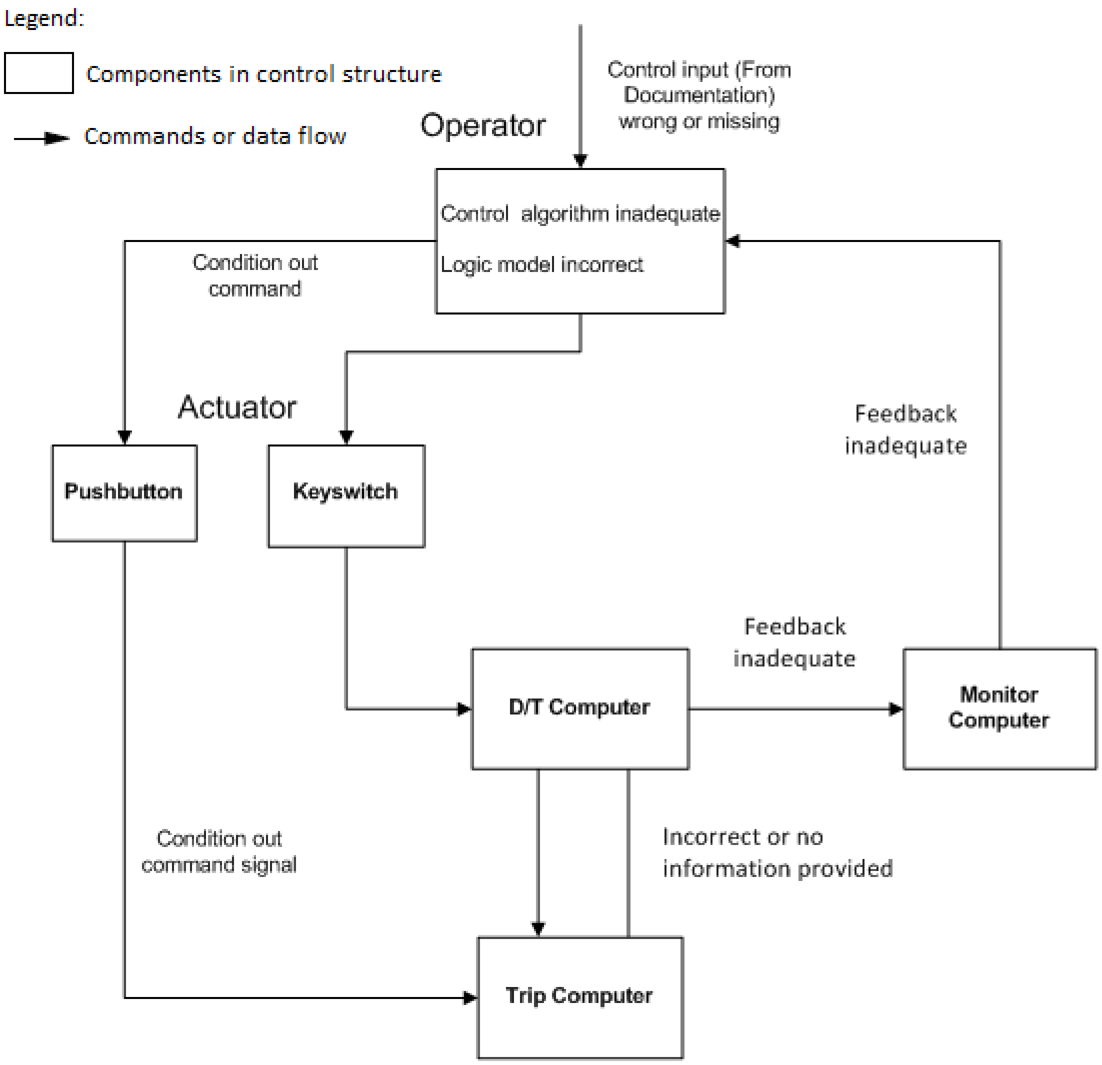


Figure 5.6: Causal factors leading to hazard c1

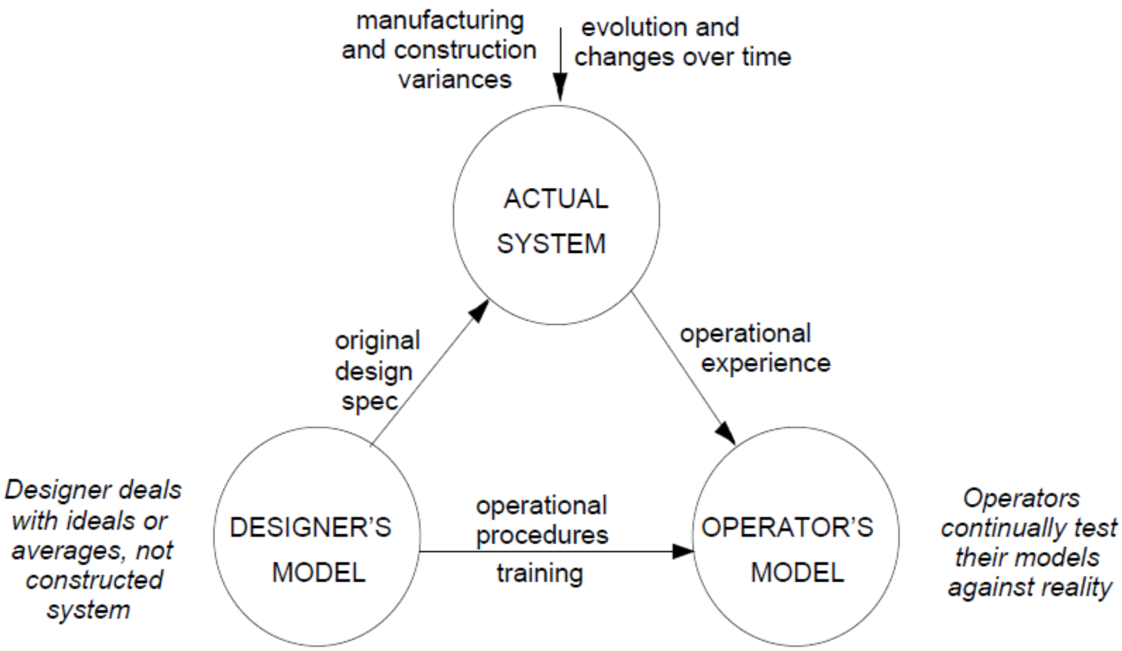
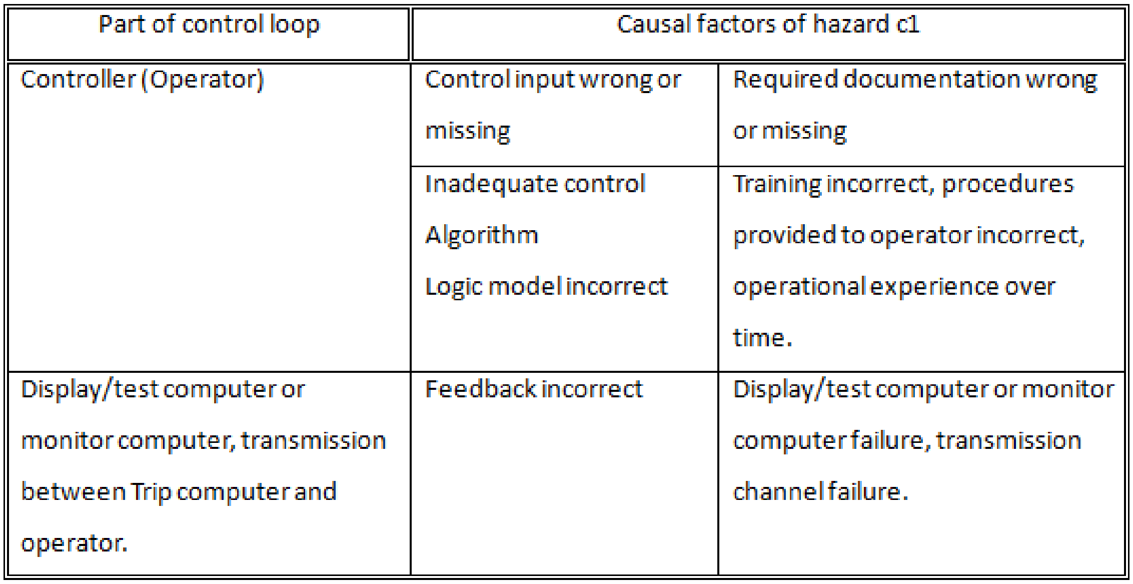
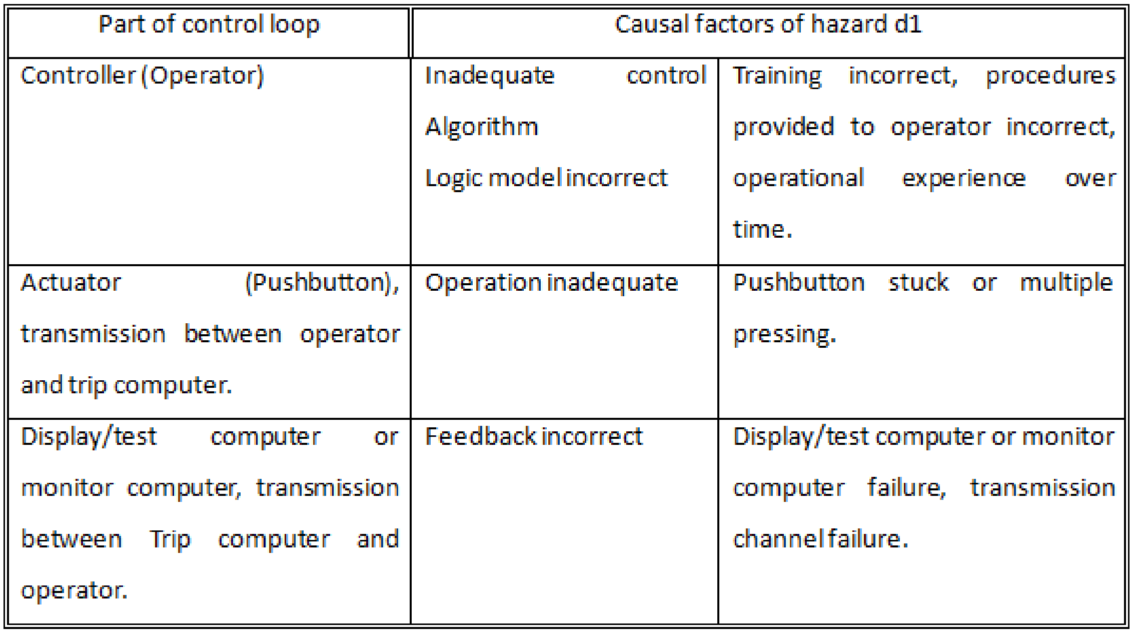

manufacturing and construction variances
evolution and changes over time
ACTUAL SYSTEM
original design spec
operational experience
Designer deals with ideals or averages, not constructed system
DESIGNER'S MODEL
operational procedures
training
OPERATOR'S MODEL
Operators continually test their models against reality

Figure 5.7: The relationship between mental models (Leveson, 2011)



Part of control loop	Causal factors of hazard c1	
Controller (Operator)	Control input wrong or missing	Required documentation wrong or missing
	Inadequate control Algorithm Logic model incorrect	Training incorrect, procedures provided to operator incorrect, operational experience over time.
Display/test computer or monitor computer, transmission between Trip computer and operator.	Feedback incorrect	Display/test computer or monitor computer failure, transmission channel failure.

Figure 5.8: Causal factors of hazard c1

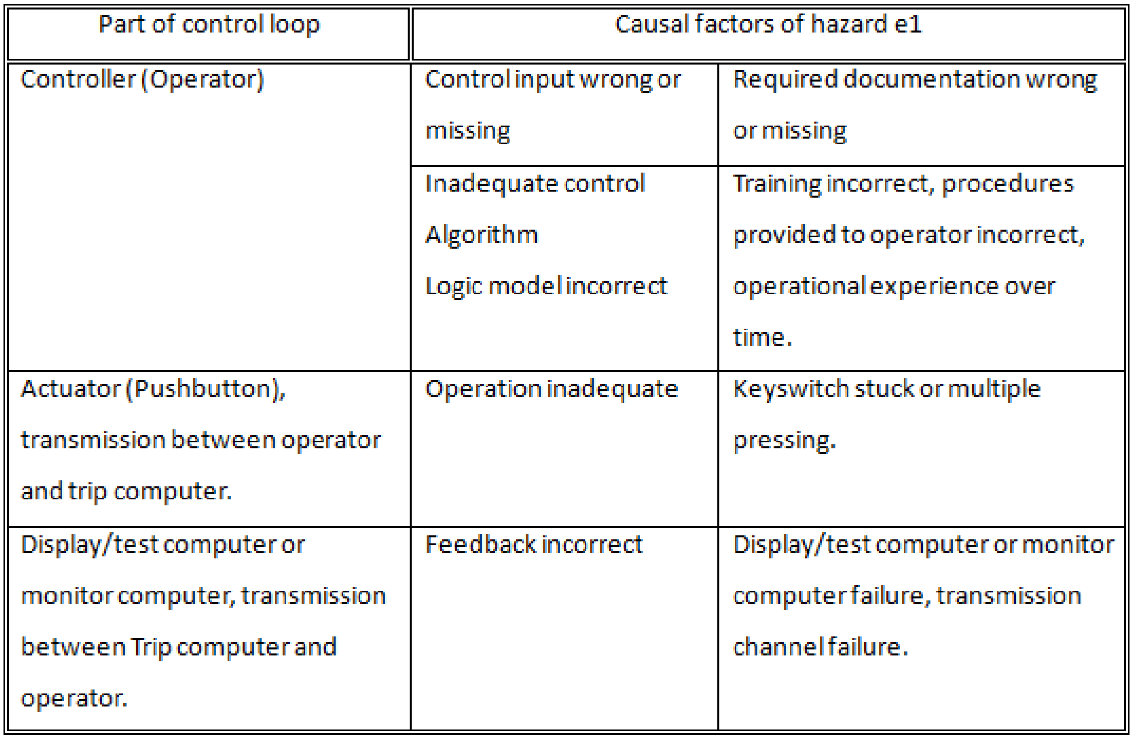


Part of control loop	Causal factors of hazard d1	
Controller (Operator)	Inadequate control Algorithm Logic model incorrect	Training incorrect, procedures provided to operator incorrect, operational experience over time.
Actuator (Pushbutton), transmission between operator and trip computer.	Operation inadequate	Pushbutton stuck or multiple pressing.
Display/test computer or monitor computer, transmission between Trip computer and operator.	Feedback incorrect	Display/test computer or monitor computer failure, transmission channel failure.

Figure 5.9: Causal factors of hazard d1

Now, we are going to analyze the hazard b1 – "Watchdog fails to send a watchdog trip when it does not meet time-out requirement". According to the design specification, the watchdog can only send the watchdog trip when the update signal is missing for a specified period. So in this case, the watchdog acts as a controller. There is no control input from the trip computer or operator as well as no feedback from the sensor. The processes of hazard b1 analysis are similar to those of hazard a1. Figure 5.11 shows the causal factors of hazard b1.

Compared with hazard a1 and b1, hazard a2 is quite different. Hazard a2 and b2 refer to control actions that occur incorrectly rather than required control actions that do not occur. The analysis of hazard a2 and b2 is similar to that of hazard c1. For the analysis of hazard a2, we will omit causal factors related to the actuator and controlled process because they will not lead to hazard a2. Figure 5.12 shows the

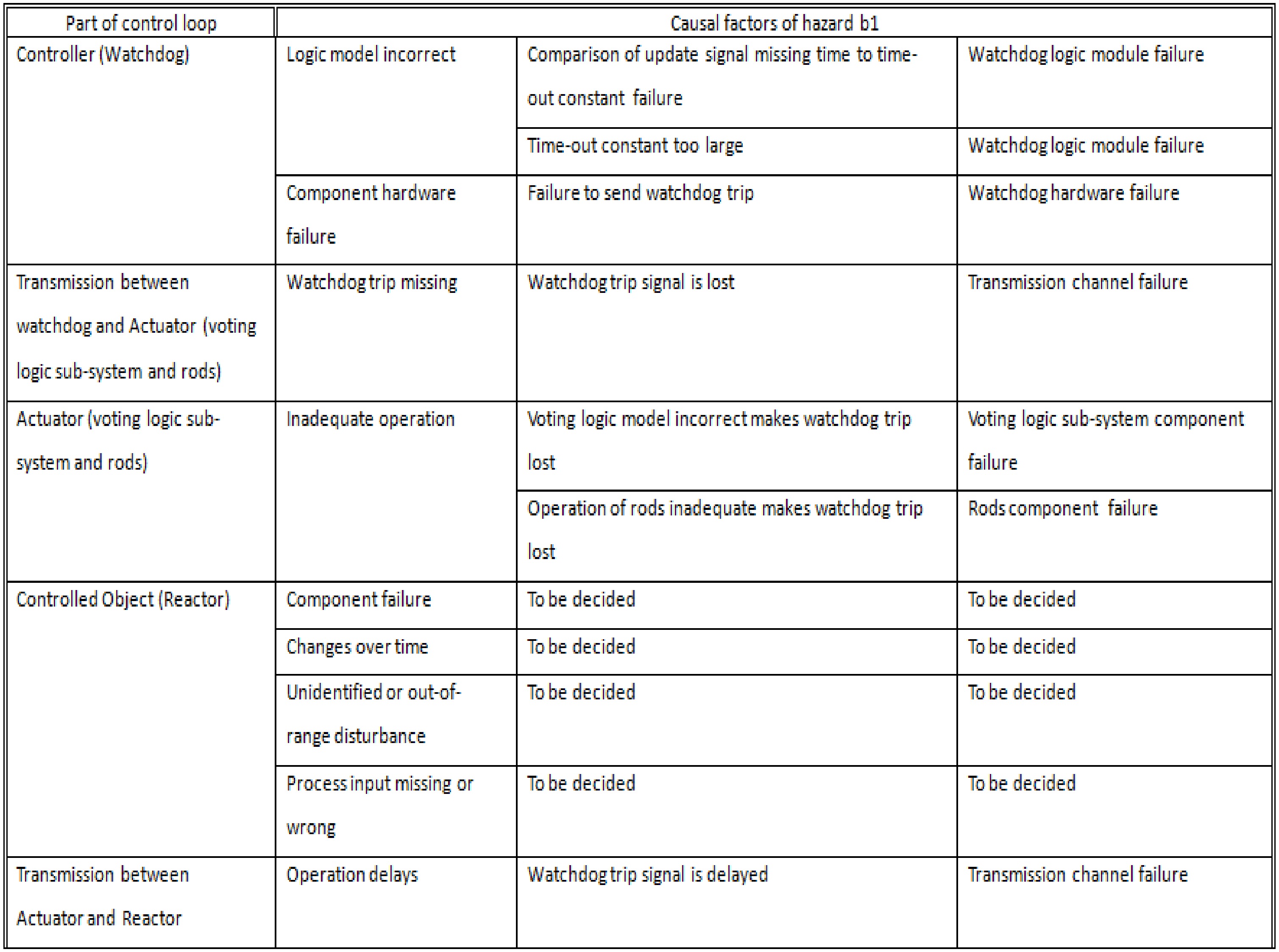


Part of control loop	Causal factors of hazard e1	
Controller (Operator)	Control input wrong or missing	Required documentation wrong or missing
	Inadequate control Algorithm Logic model incorrect	Training incorrect, procedures provided to operator incorrect, operational experience over time.
Actuator (Pushbutton), transmission between operator and trip computer.	Operation inadequate	Keyswitch stuck or multiple pressing.
Display/test computer or monitor computer, transmission between Trip computer and operator.	Feedback incorrect	Display/test computer or monitor computer failure, transmission channel failure.

Figure 5.10: Causal factors of hazard e1

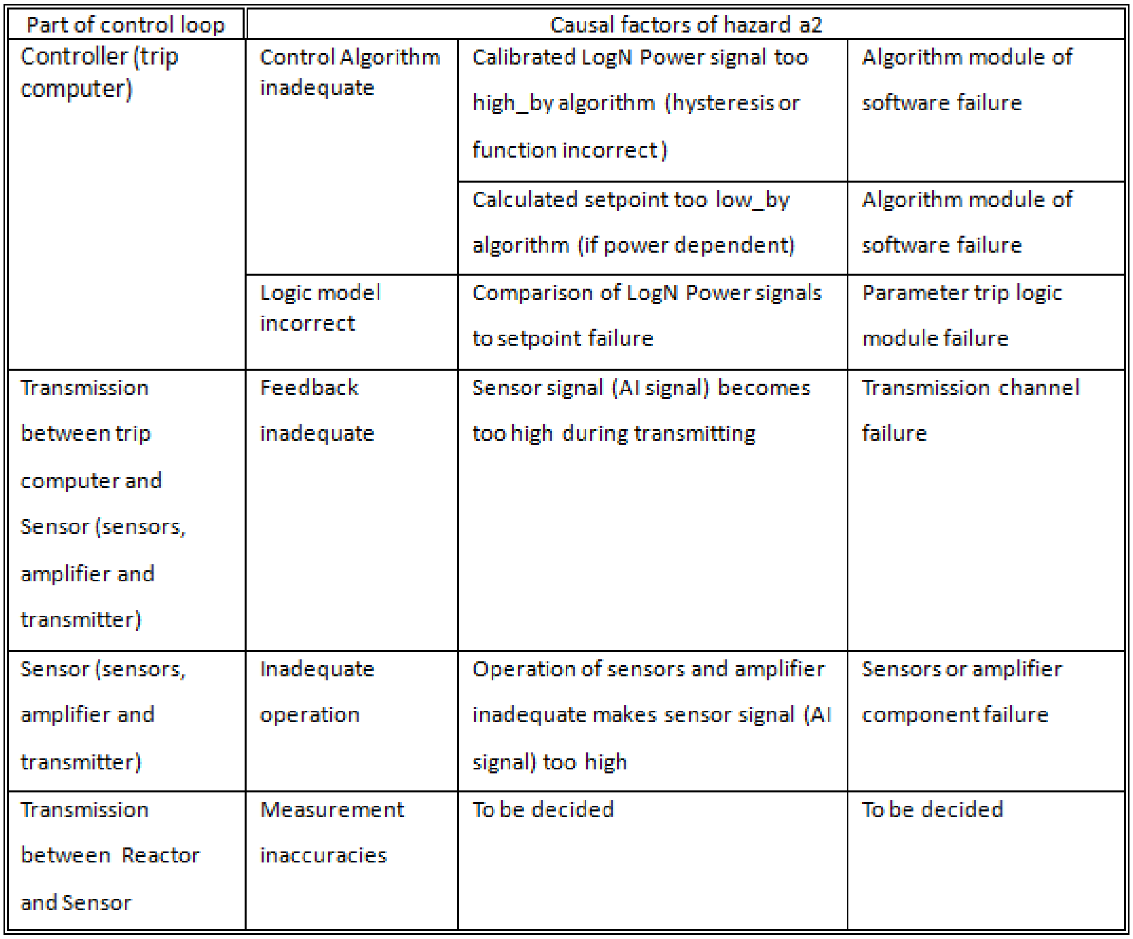
causal factors of hazard a2. For hazard b2, it is simpler because there is no feedback from the sensor for the watchdog. Figure 5.13 shows the causal factors of hazard b2.

To compare with the original FMEA results easily, we put the results based on STPA into the FMEA worksheet. In the function column, it is High LogN Power Trip in single channel. Then the highest failure modes should be hazard a1, b1, a2 and b2. The causal factors of each hazard are composed from the lower level failure modes. The causal factors in the lowest level are the failure causes in FMEA. Figure 5.14 shows the results based on STPA for SDS1.



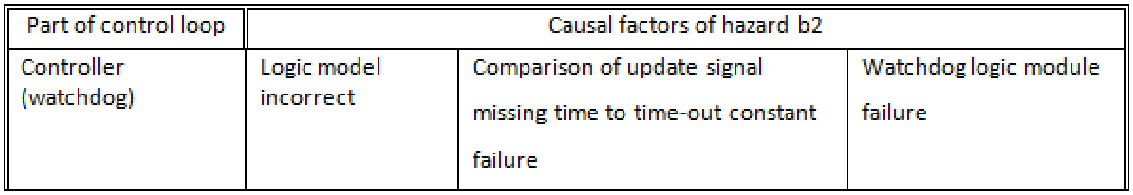
Part of control loop	Causal factors of hazard b1		
Controller (Watchdog)	Logic model incorrect	Comparison of update signal missing time to time-out constant failure	Watchdog logic module failure
		Time-out constant too large	Watchdog logic module failure
	Component hardware failure	Failure to send watchdog trip	Watchdog hardware failure
Transmission between watchdog and Actuator (voting logic sub-system and rods)	Watchdog trip missing	Watchdog trip signal is lost	Transmission channel failure
Actuator (voting logic sub-system and rods)	Inadequate operation	Voting logic model incorrect makes watchdog trip lost	Voting logic sub-system component failure
		Operation of rods inadequate makes watchdog trip lost	Rods component failure
Controlled Object (Reactor)	Component failure	To be decided	To be decided
	Changes over time	To be decided	To be decided
	Unidentified or out-of-range disturbance	To be decided	To be decided
	Process input missing or wrong	To be decided	To be decided
Transmission between Actuator and Reactor	Operation delays	Watchdog trip signal is delayed	Transmission channel failure

Figure 5.11: Causal factors of hazard b1



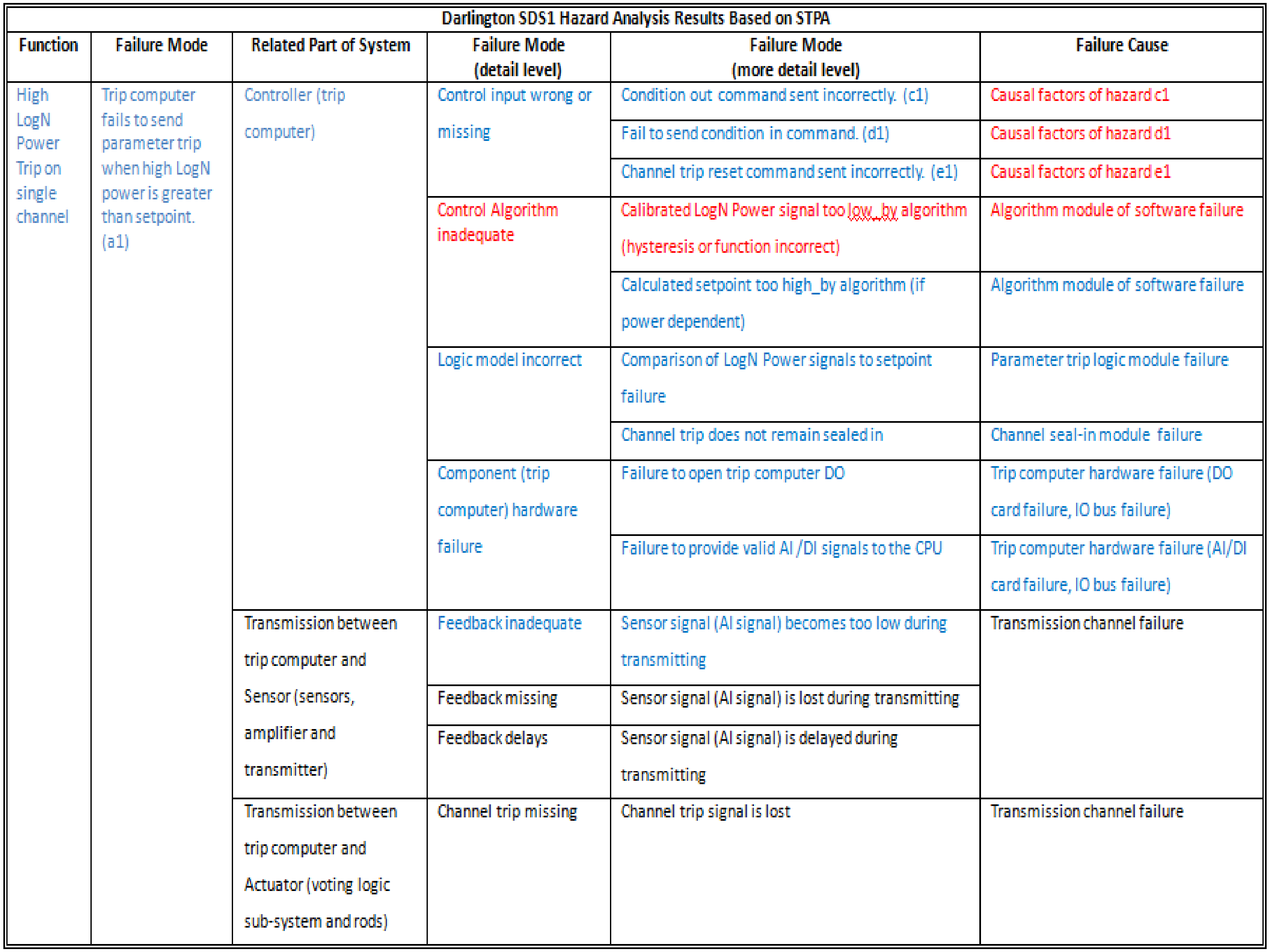
Part of control loop	Causal factors of hazard a2		
Controller (trip computer)	Control Algorithm inadequate	Calibrated LogN Power signal too high_by algorithm (hysteresis or function incorrect)	Algorithm module of software failure
		Calculated setpoint too low_by algorithm (if power dependent)	Algorithm module of software failure
	Logic model incorrect	Comparison of LogN Power signals to setpoint failure	Parameter trip logic module failure
Transmission between trip computer and Sensor (sensors, amplifier and transmitter)	Feedback inadequate	Sensor signal (AI signal) becomes too high during transmitting	Transmission channel failure
Sensor (sensors, amplifier and transmitter)	Inadequate operation	Operation of sensors and amplifier inadequate makes sensor signal (AI signal) too high	Sensors or amplifier component failure
Transmission between Reactor and Sensor	Measurement inaccuracies	To be decided	To be decided

Figure 5.12: Causal factors of hazard a2



Part of control loop	Causal factors of hazard b2		
Controller (watchdog)	Logic model incorrect	Comparison of update signal missing time to time-out constant failure	Watchdog logic module failure

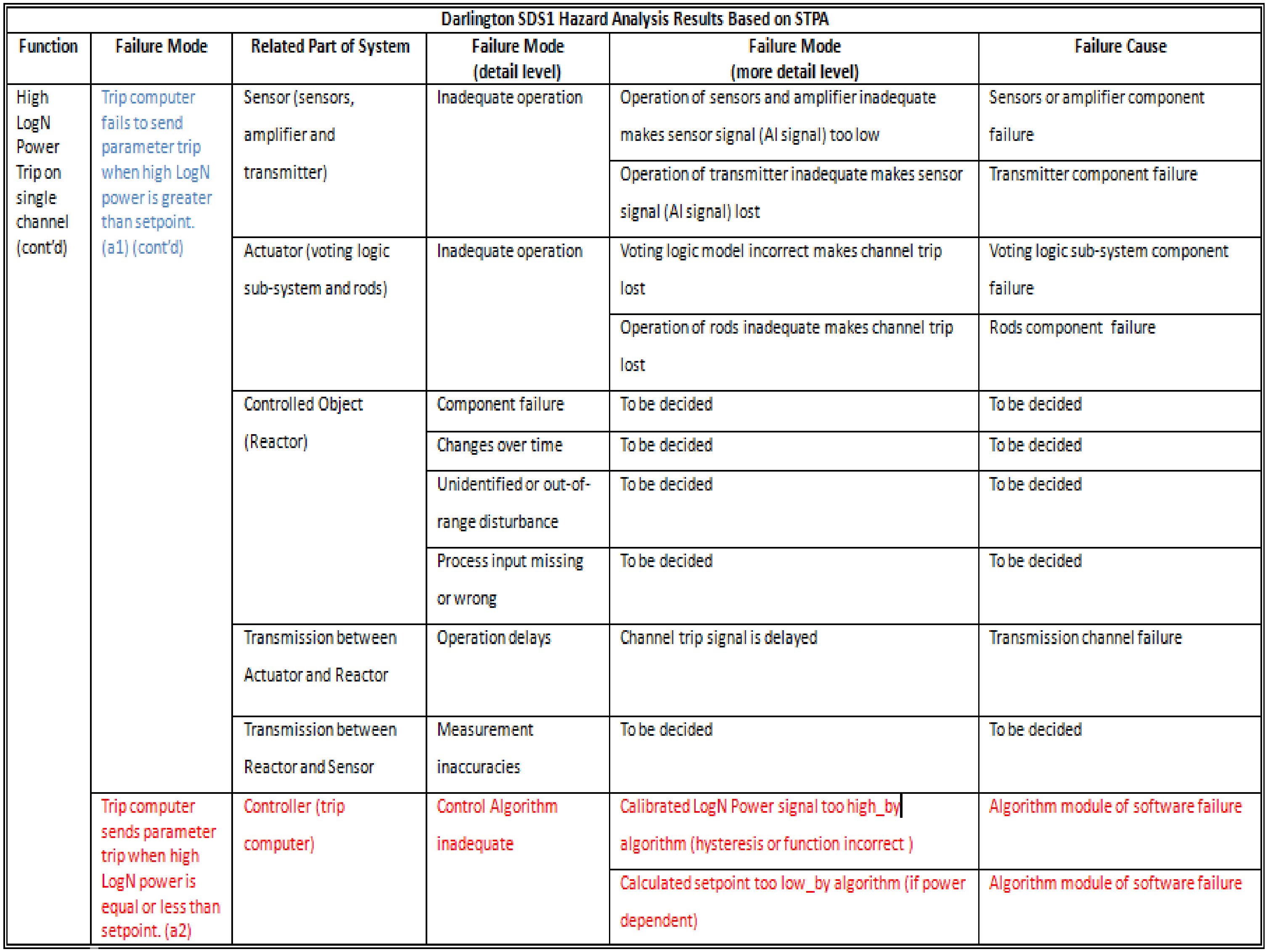
Figure 5.13: Causal factors of hazard b2



Darlington SDS1 Hazard Analysis Results Based on STPA

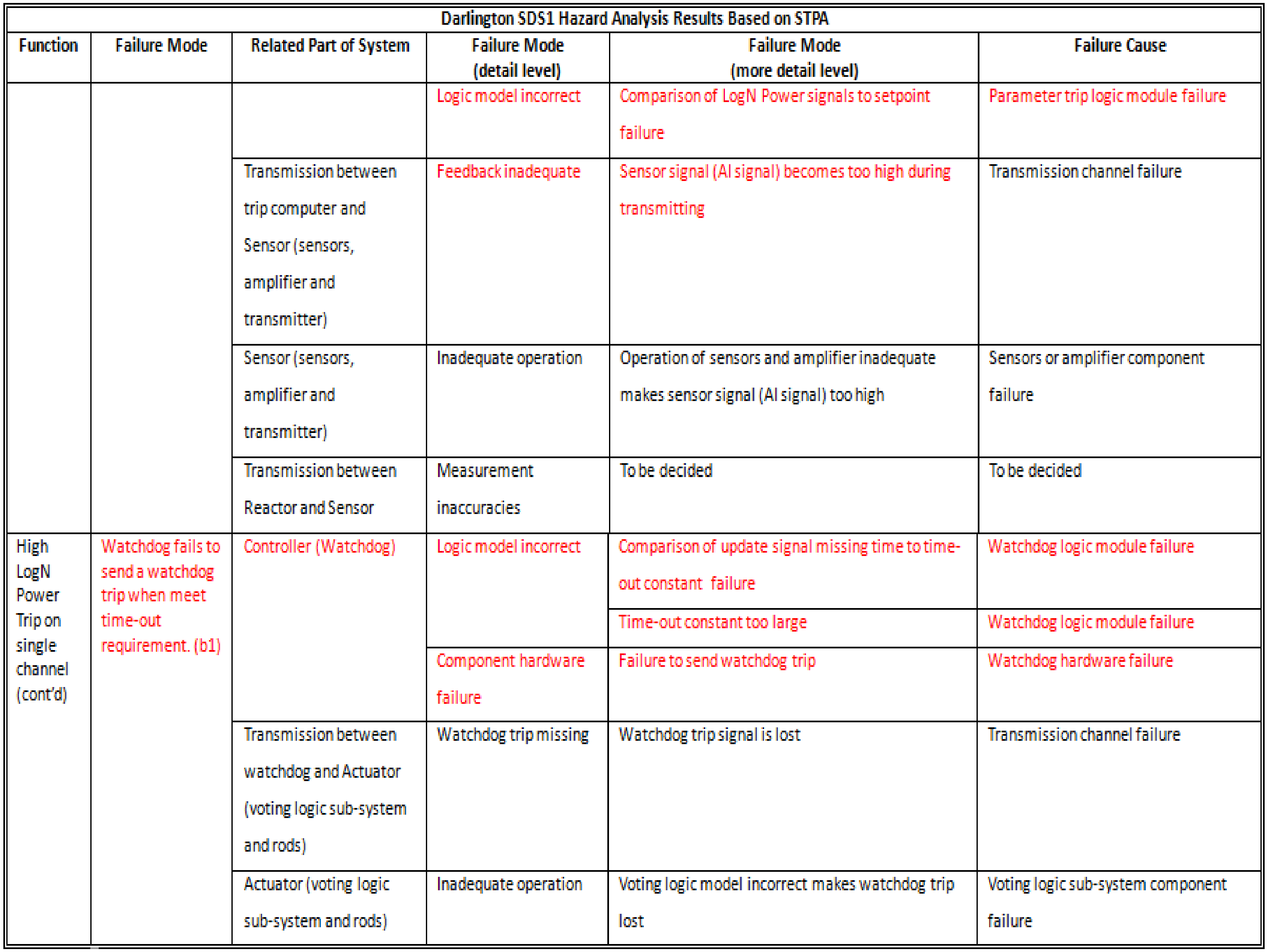
Function	Failure Mode	Related Part of System	Failure Mode (detail level)	Failure Mode (more detail level)	Failure Cause
High LogN Power Trip on single channel	Trip computer fails to send parameter trip when high LogN power is greater than setpoint. (a1)	Controller (trip computer)	Control input wrong or missing	Condition out command sent incorrectly. (c1)	Causal factors of hazard c1
				Fail to send condition in command. (d1)	Causal factors of hazard d1
				Channel trip reset command sent incorrectly. (e1)	Causal factors of hazard e1
			Control Algorithm inadequate	Calibrated LogN Power signal too low_by algorithm (hysteresis or function incorrect)	Algorithm module of software failure
				Calculated setpoint too high_by algorithm (if power dependent)	Algorithm module of software failure
			Logic model incorrect	Comparison of LogN Power signals to setpoint failure	Parameter trip logic module failure
				Channel trip does not remain sealed in	Channel seal-in module failure
			Component (trip computer) hardware failure	Failure to open trip computer DO	Trip computer hardware failure (DO card failure, IO bus failure)
				Failure to provide valid AI /DI signals to the CPU	Trip computer hardware failure (AI/DI card failure, IO bus failure)
		Transmission between trip computer and Sensor (sensors, amplifier and transmitter)	Feedback inadequate	Sensor signal (AI signal) becomes too low during transmitting	Transmission channel failure
			Feedback missing	Sensor signal (AI signal) is lost during transmitting	
			Feedback delays	Sensor signal (AI signal) is delayed during transmitting	
		Transmission between trip computer and Actuator (voting logic sub-system and rods)	Channel trip missing	Channel trip signal is lost	Transmission channel failure

Figure 5.14: Darlington SDS1 Hazard Analysis Results Based on STPA



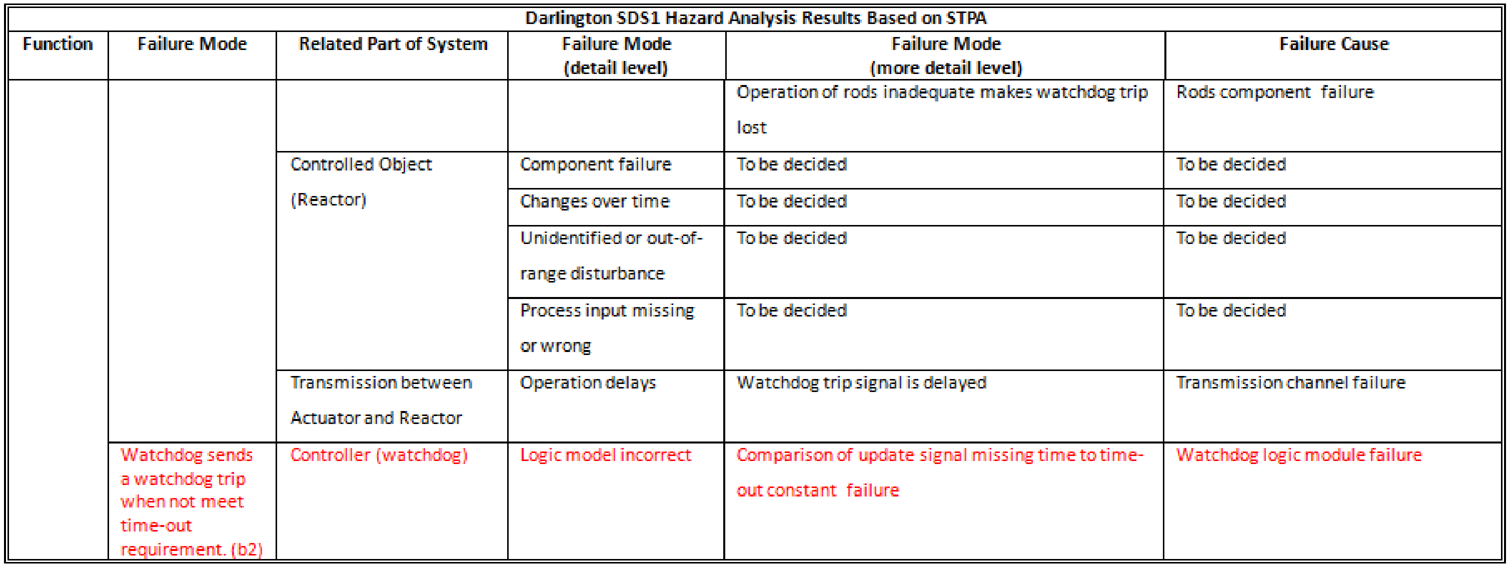
Darlington SDS1 Hazard Analysis Results Based on STPA

Function	Failure Mode	Related Part of System	Failure Mode (detail level)	Failure Mode (more detail level)	Failure Cause
High LogN Power Trip on single channel (cont'd)	Trip computer fails to send parameter trip when high LogN power is greater than setpoint. (a1) (cont'd)	Sensor (sensors, amplifier and transmitter)	Inadequate operation	Operation of sensors and amplifier inadequate makes sensor signal (AI signal) too low	Sensors or amplifier component failure
				Operation of transmitter inadequate makes sensor signal (AI signal) lost	Transmitter component failure
		Actuator (voting logic sub-system and rods)	Inadequate operation	Voting logic model incorrect makes channel trip lost	Voting logic sub-system component failure
				Operation of rods inadequate makes channel trip lost	Rods component failure
		Controlled Object (Reactor)	Component failure	To be decided	To be decided
			Changes over time	To be decided	To be decided
			Unidentified or out-of-range disturbance	To be decided	To be decided
			Process input missing or wrong	To be decided	To be decided
		Transmission between Actuator and Reactor	Operation delays	Channel trip signal is delayed	Transmission channel failure
		Transmission between Reactor and Sensor	Measurement inaccuracies	To be decided	To be decided
	Trip computer sends parameter trip when high LogN power is equal or less than setpoint. (a2)	Controller (trip computer)	Control Algorithm inadequate	Calibrated LogN Power signal too high_by algorithm (hysteresis or function incorrect)	Algorithm module of software failure
				Calculated setpoint too low_by algorithm (if power dependent)	Algorithm module of software failure



Darlington SDS1 Hazard Analysis Results Based on STPA

Function	Failure Mode	Related Part of System	Failure Mode (detail level)	Failure Mode (more detail level)	Failure Cause
			Logic model incorrect	Comparison of LogN Power signals to setpoint failure	Parameter trip logic module failure
		Transmission between trip computer and Sensor (sensors, amplifier and transmitter)	Feedback inadequate	Sensor signal (AI signal) becomes too high during transmitting	Transmission channel failure
		Sensor (sensors, amplifier and transmitter)	Inadequate operation	Operation of sensors and amplifier inadequate makes sensor signal (AI signal) too high	Sensors or amplifier component failure
		Transmission between Reactor and Sensor	Measurement inaccuracies	To be decided	To be decided
High LogN Power Trip on single channel (cont'd)	Watchdog fails to send a watchdog trip when meet time-out requirement. (b1)	Controller (Watchdog)	Logic model incorrect	Comparison of update signal missing time to time-out constant failure	Watchdog logic module failure
				Time-out constant too large	Watchdog logic module failure
			Component hardware failure	Failure to send watchdog trip	Watchdog hardware failure
		Transmission between watchdog and Actuator (voting logic sub-system and rods)	Watchdog trip missing	Watchdog trip signal is lost	Transmission channel failure
		Actuator (voting logic sub-system and rods)	Inadequate operation	Voting logic model incorrect makes watchdog trip lost	Voting logic sub-system component failure



Darlington SDS1 Hazard Analysis Results Based on STPA

Function	Failure Mode	Related Part of System	Failure Mode (detail level)	Failure Mode (more detail level)	Failure Cause
				Operation of rods inadequate makes watchdog trip lost	Rods component failure
		Controlled Object (Reactor)	Component failure	To be decided	To be decided
			Changes over time	To be decided	To be decided
			Unidentified or out-of-range disturbance	To be decided	To be decided
			Process input missing or wrong	To be decided	To be decided
		Transmission between Actuator and Reactor	Operation delays	Watchdog trip signal is delayed	Transmission channel failure
	Watchdog sends a watchdog trip when not meet time-out requirement. (b2)	Controller (watchdog)	Logic model incorrect	Comparison of update signal missing time to time-out constant failure	Watchdog logic module failure

Note:
Red: Identified by STPA results only.
Blue: Identified by both original FMEA results and STPA results.
Black: Not related with trip computer.

5.3 Comparison Between the Results Based on STPA and the Original Darlington FMEA Results

To determine the usefulness of STPA as a method for the Darlington shutdown system hazard analysis, the FEMA results based on STPA analysis (figure 5.14) are compared with the original Darlington FMEA results under the same function "High LogN Power Trip on single channel". The original Darlington FMEA results cannot be shown for confidential reasons, but they are essentially the same as the ones marked as identified in both FMEA and STPA. The conclusions from the comparison are described as follows.

Clear guidance

In most cases, there is no unified standard to let people know how to identify hazard, failure mode and failure cause in FMEA. Usually analyst has to use professional knowledge and experience. This situation might make it difficult for other people to understand how the analysis report is structured and what failure mode might be missed. However, STPA provides clear guidance for an analyst to develop a hazard analysis. Figure 5.14 shows us that hazard analysis is well guided by using STPA. STPA has clear steps for the analyst to follow. These steps are: selecting the specific function; drawing the control structure for the system; identifying the related potentially inadequate control actions (hazards); and identifying the causal factors.

More hazards and failure modes identified

By using STPA in our case, more hazards, failure modes and causal factors are identified, but the additional ones identified were not significant and do not affect the conclusions presented in the original report. In figure 5.14, items in red refer to those identified by STPA only; blue refers to those identified by both; black refers to those that are not related with the trip computer. The results indicate that not only more hazards, failure modes and causal factors related to the trip computer were identified, but more components and their interactions were considered. This is because STPA analyzes hazards and causal factors in a systematic way. It considers not only components themselves, but also the interactions among components or between operator and components. By using a safety control structure and a general control flaws classification to analyze causal factors of each identified hazard, STPA may help the analyst to find more failure modes and causal factors.

Good extension

Figure 5.14 includes three nested tables (figure 5.8, figure 5.9 and figure 5.10), because the trip computer exists in another control structure. In STPA, if any component in the control structure is complex such that it has its own logic or algorithm model, or even its own control structure, or it exists in another control structure, it can be further developed by following the same process. In our example, “voting logic sub-system” can be further developed because it has its own logic model.

5.4 Case Study Conclusion

This case study provided a sample of hazard analysis for one function of the Darlington SDS1 based on STPA. The main purpose of this thesis is to examine how to use a systemic way to implement hazard analysis.

We used STPA to identify the related hazards, created the safety control structure and identified the related causal factors. Finally we compared the results based on STPA with the original FMEA results. In our case, we demonstrated how to apply STPA to hazard analysis. We think that STPA provides a different idea and way to develop hazard analysis, compared with traditional methods. It is worthwhile to try to use it for hazard analysis in different domains. We are also confident that our FMEA results based on STPA analysis provide more useful analysis information, compared with the original Darlington version of FMEA results.

At the same time, it is important to note that the information generated by STPA did not uncover hazards that had been ignored in the original Darlington Shutdown Systems. A key principle in developing such safety systems is the principle of *defence-in-depth*. This means that other analyses were performed, especially in the context of nuclear safety analyses, and the additional information provided now by STPA was already taken into account through these other processes. The advantage of STPA is that it will add to our ability to provide a *defence-in-depth* regime, since the hazards analysis process using STPA will enhance our ability to uncover system level (environment and operator) potential hazards.

Chapter 6

Conclusions and Future Work

This chapter draws conclusions for the thesis, and makes suggestions for future work.

6.1 Conclusions

This is the first time that STPA has been applied to a Darlington shutdown system. Also, this might be the first time STPA is applied in the nuclear domain. Some conclusions can be drawn from this work:

- Existing hazard analysis approaches such as FTA and FMEA have been used for a long period. As demonstrated in earlier chapters, we now realize that these methods have some limitations. These limitations are of primary concern for complex systems, and STPA may have some advantages for such systems.

- STPA provides a systemic methodology for hazard analysis as well as clear guidance for conducting a hazard analysis.

- STPA is usually used at the system level, but it can also be extended for more detailed levels.

- The results based on STPA analysis include not only component failures but also the interaction failures among components or between components and human operators within a hierarchical structure.

- Although it has many advantages, STPA still has some subjective aspects. For different people, safety control structure might be different because their understanding of the system might be different. The identification of hazards and causal factors also might be different. The more you understand the system, the more hazards and causal factors you may find and the more accurate and useful they could be.

- Like all the other approaches for hazard analysis, STPA cannot provide a proof for completeness and accuracy of identification of hazards and causal factors.

6.2 Future work

More work and improvement is always necessary in the future to continue this work. Some of them are listed below.

- In terms of the case study, further analysis can be made for the whole system. Due to documentation unavailability, we only developed a small example to demonstrate how to use STPA. If more material is available, each component in the system-level control structure could be further developed if it had its own logic model, or even its own control structure, or if it existed in another control structure.

- A tool could be developed to help the analyst create control structures and automate hazards and causal factors results. Since STPA is a new method, and mature tool support is lacking. Development of such a tool would be extremely useful for people working on safety-critical systems.

- The general classification for identifying potentially inadequate control actions might be improved as well as the classification of control flaws for identifying causal factors.

- More research could be conducted to ‘prove’ the completeness and accuracy of identification of hazards and causal factors. Since STPA is based on a control structure, it might be helpful to use some knowledge related with control theory.

Bibliography

Ashby, W. R. (1956). *An Introduction to Cybernetics.* Chapman and Hall.

Bertsche, B. (2008). *Reliability in Automotive and Mechanical Engineering.* VDI-Buc.

Bowman, W. C., Archinoff, G. H., Raina, V. M., and Tremaine, D. R. (2000). An Application of Fault Tree Analysis to Safety Critical Software at Ontario Hydro. In *Probabilistic Safety Assessment and Management (PSAM).*

Broadbent, D. E., Reason, J., and Baddeley, A. (1990). *Human Factors in Hazardous Situations.* Clarendon Press.

Coppit, D., Sullivan, K., and Dugan, J. B. (2000). Formal Semantics of Models for Computational Engineering: A Case Study on Dynamic Fault Trees. In *Software Reliability Engineering, 2000. ISSRE 2000. Proceedings. 11th International Symposium on*, pages 270–282.

Ericson, C. A. (2005). *Hazard Analysis Techniques for System Safety.* John Wiley & Sons, Inc.

Fussell, J. B. and Vesely, W. E. (1972). A New Method for Obtaining Cutsets for Fault Trees. *Trans. ANS*, pages 262–263.

Goddard, P. L., Raytheon, and Troy (2000). Software FMEA Techniques. In *Reliability and Maintainability Symposium, 2000.*, pages 118–123.

Guentcheva, D., Yu, X., and Diguer, D. (2002). Darlington NGD Loss of Flow Trip Coverage Project-SDS2 Hazards Analysis Report. Technical report, Ontario Power Generation (OPG).

Gusterson, H. (2011). The lessons of Fukushima. *Bulletin of the Atomic Scientist*.

Hollnagel, E. (2004). *Barriers and Accident Prevention*. Ashgate Publishing Limited.

Hollnagel, E. and Goteman, O. (2004). The Functional Resonance Accident Model. In *Cognitive Systems Engineering in Process Control, 2004*.

Hollnagel, E., Pruchnicki, S., Woltjer, R., and Etcher, S. (2008). Analysis of Comair flight 5191 with the Functional Resonance Accident Model. In *International Symposium of the Australian Aviation Psychology Association AAvPA, 2008*.

Huang, G. Q., Shi, J., and Mak, K. L. (2000). Failure Mode and Effect Analysis (FMEA) Over the WWW. *The International Journal of Advanced Manufacturing Technology*, **16**(8), 603–608.

H.W.Heinrich (1931). *Industrial Accident Prevention: A Scientific Approach*. McGraw-Hill.

Ishimatsu, T., Leveson, N. G., Thomas, J., Katahira, M., Miyamoto, Y., and Nakao, H. (2010). Modeling and Hazard Analysis Using STPA. In *International Association for the Advancement of Space Safety, 2010*.

Leplat, J. (1984). Occupational Accident Research and Systems Approach. *Occupational Accidents*, **6**, 77–89.

Leveson, N. G. (1995a). Safety as a System Property. *Communications of the ACM*, **38**.

Leveson, N. G. (1995b). *Safeware: System Safety and Computers.* Addison-Wesley.

Leveson, N. G. (2004). A New Accident Model for Engineering Safer Systems. *Safety Science*, **42**(4).

Leveson, N. G. (2011). *Engineering a Safer World.* Engineering Systems. The MIT Press.

Leveson, N. G., Cha, S., and Shimeall, T. (1991). Safety Verification of Ada Programs Using Software Fault Trees. *IEEE Software*, **8**(4), 48–59.

Misra, K. B. (2008). *Handbook of Performability Engineering*, volume 38. Springer, 1st edition.

Parnas, D. L., van Schouwen, A. J., and Kwan, S. P. (1990). Evaluation of Safety-Critical Software. *Communications of the ACM*, **33**.

Rasmussen, J. and Svedung, I. (2000). *Proactive Risk Management in a Dynamic Society.* Swedish Rescue Services Agency, 1st edition.

Stamatelatos, M. and Vesely, W. (2002). *Fault Tree Handbook with Aerospace Applications.* NASA Office of Safety and Mission Assurance.

U.S.A. Department of Defense (1980). *MIL-STD80-1629A: Procedures for Performing a Failure Mode, Effects and Criticality Analysis.* U.S.A. Department of Defense.

U.S.A. Department of Defense (2000). *MIL-STD80-882D: Standard Practice for System Safety*. U.S.A. Department of Defense.

Vesely, W. E., Goldberg, F. F., Roberts, N. H., and Haasl, D. F. (1981). *Fault Tree Handbook*. U.S. Nuclear Regulatory Commission.

Weber, W., Tondok, H., and Bachmayer, M. (2003). Enhancing Software Safety by Fault Trees: Experiences from an Application to Flight Critical SW. *In Knowledge-Based Intelligent Information and Engineering Systems*, **2788**, 289–302.

Wong, A., Lau, D., M.Viola, and Black, R. (2007). Darlington GSA Design Requirements for SDS1 Trip Computer System. Technical Report NK38-DID-68200-001, Revision 008, Ontario Power Generation (OPG).

Yu, X., Webb, N., and Diguer, D. (2002). Darlington NGD Loss of Flow Trip Coverage Project-SDS1 Hazards Analysis Report. Technical report, Ontario Power Generation (OPG).