ABSTRACT

Title of Document: ON THE THEORETICAL FOUNDATIONS AND PRINCIPLES OF ORGANIZATIONAL SAFETY RISK ANALYSIS

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This research covers a targeted review of relevant theories and technical domains related to the incorporation of organizational factors into technological systems risk. In the absence of a comprehensive set of principles and modeling guidelines rooted in theory and empirical studies, all models look equally good, or equally poor, with very little basis to discriminate and build confidence. Therefore, this research focused on the possibility of improving the theoretical *foundations* and *principles* for the field of *Organizational Safety Risk Analysis*. Also, a process for adapting a *hybrid* modeling technique, in order to operationalize the theoretical organizational safety frameworks, is proposed. Candidate ingredients are techniques from Risk Assessment, Human Reliability, Social and Behavioral Science, Business Process Modeling, and Dynamic Modeling. Then, as a realization of aforementioned modeling principles, an organizational safety risk

framework, named *Socio-Technical Risk Analysis (SoTeRiA)*[1] is developed. The proposed framework considers the theoretical relation between organizational safety culture, organizational safety structure/practices, and organizational safety climate, with specific distinction between safety culture and safety climate. A systematic view of safety culture and safety climate fills an important gap in modeling complex system safety risk, and thus the proposed organizational safety risk theory describing the theoretical relation between two concepts to bridge this gap. In contrast to the current safety causal models which do not adequately consider the multilevel nature of the issue, the proposed multilevel causal model explicitly recognizes the relationships among constructs at multiple levels of analysis. Other contributions of this research are in implementing the proposed organizational safety framework in the aviation domain, particularly the airline maintenance system. The US Federal Aviation Administration (FAA), which has sponsored this research over the past three years, has recognized the issue of organizational factors as one of the most critical questions in the quest to achieve 80% reduction in aviation accidents. An example of the proposed hybrid modeling environment including an integration of System Dynamics (SD), Bayesian Belief Network (BBN), Event Sequence Diagram (ESD), and Fault Tree (FT), is also applied in order to demonstrate the value of hybrid frameworks. This hybrid technique integrates deterministic and probabilistic modeling perspectives, and provides a flexible risk management tool.

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[1] Soteria was the goddess of safety, and of deliverance and preservation from harm in Greek mythology.

ON THE THEORETICAL FOUNDATIONS AND PRINCIPLES OF ORGANIZATIONAL SAFETY RISK ANALYSIS

by

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I dedicate this work

to

my parents,

without whose unstinting love and devoted care

none of this

would have become possible

Z.M.

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1. INTRODUCTION

1.1 Motivation

In most modern industries, safety is a stated goal at the same level of priority as efficient and economical production. Yet we continue to witness large-scale system failures and loss of lives due to major accidents. Many such failures and accidents do not have a simple explanation, particularly those that have significant contributions from human and organizational behaviors. One example of these major accidents is the Chernobyl accident in 1996, for which the International Atomic Energy Agency cites "poor safety culture" as a primary cause. (Cox & Flin, 1998) As another example, after the crash of Continental Express Flight 2574 near Eagle Lakes, Texas, on September 11, 1991, the National Transportation Safety Board (NTSB) stated that Continental Express management's failure "to establish a corporate culture which encouraged and enforced adherence to approved maintenance and quality assurance procedures" (NTSB/AAR-92/04, 1992:54) was a contributing factor.

Increasing interest over the past two decades in causal modeling of organizational safety behavior is in part motivated by the desire to understand the deeper more fundamental causes of accidents and incidents. Naturally the main objective is to be able to identify preventive measures and assess their effectiveness. Complex socio-technical systems are comprised of two different key ingredients: physical system and human system. Gordon (1998) among an increasing number of researchers remind us that, "the performance of a complex socio-technical system is dependent on the interaction of technical, human, social, organizational, managerial and environmental factors…" However there are significant gaps in this multidisciplinary research area. Social Sciences fail to provide an understanding of the processes that lead to failures in technological systems, while engineers fail to incorporate social aspects in the analysis of conditions that lead to system failures. Human Reliability Analysis which is the study of the nature, causes, and probability of human actions in the design and operation of systems and processes, is concentrated on individual error and is not typically extended to formally consider the effects of organizational factors , in a formal and comprehensive way as well. As Reason (1990) states "While cognitive psychology can tell us something about an individual's potential for error, it has very little to say about how these individual tendencies interact within complex groupings of people working in high–risk systems". And it is these "collective failures" that represents the major residual hazard. Organizations (behind the technical system), where these "collective failures" may occur, play a significant role in the reliability of technological systems.

At the same time, new realities highlight the need for more comprehensive models of risk assessments and management. These include rapid changes in technology, changes in the nature of accidents, new types of hazards, complexity of rare, but high consequence accidents, and changing regulatory approaches to safety. (Leveson, 2004)

The key questions in this line of research can be summarized as follows: (1) what are the organizational factors that affect risk? (2) how do these factors influence risk? and (3) how much do they contribute to risk? This thesis aims at paving the way for more comprehensive and technically sound answers to these questions. In a broader perspective, all the efforts and studies in this research area can be placed under the banner of "*Organizational Safety Risk Analysis*". The most dominant driving forces for this field of research have been several high profile accident investigations, industry deregulation, and emergence and rapid growth of Probabilistic Risk Analysis (PRA), as a tool for decision making. The latter is the primary framework of this thesis.

Methods to perform risk assessment in the early 1960s originated in U.S. aerospace and missile programs. Later, the nuclear industry used PRA as a structured and formal method for identifying and assessing risk in its technological system. In most applications PRAs have been a tool to estimate risk as a function of equipment and operator performance. The process is used to identify potential accident scenarios, estimate the likelihoods and consequences of accidents, and improve system safety designs and operations. This analytical technique was gradually improved and applied over the past two decades, not only in the nuclear industry, but in other fields including the offshore oil, petrochemical and defense industries. However, some decision makers and safety analysts have expressed concern that the current generation of PRA may not have accounted for the contributions of organizational factors to the total risk. This is rooted, at least in part, in the fact that vast majority of PRAs do not include an explicit representation of the possible impact of organization and management on safety performance of equipment and personnel. In contrast, investigations of major accidents have cited management and organizational factors as major contributors to operational safety problems (e.g., Reason 1990). This gap between realty and safety model has motivated a number of research and modeling efforts in recent years, resulting in several methodologies and framework. This research is an effort to contribute to this new domain.

1.2 Research Approach

Seeking answers to the research questions, first, the quantitative frameworks that have been proposed for inclusion of organizational factors in PRA were studied. These research studies have mainly focused their efforts on quantification methods. Many such as MACHINE (Embrey, 1992), Omega Factor Model (Mosleh & Golfeiz, 1999), SAM (Pate-Cornell, 1996), ASRM (Luxhoj, 2004), and "Causal Modeling of Air Safety" (Roelen et al., 2003) use variations of the Bayesian Belief Network (BBN). Some other ones such as WPAM (Davoudian, 1994) utilized flow diagrams to relate work processes and organizational factors.

Significant increase in sophistication of quantitative methods of safety and risk assessment over the past two decades led many to believe that the same style of causal modeling is an effective way of assessing the effects of the organizational factor on safety risks. There is however a number of major challenges in developing a predictive causal model of organizational safety performance. The study of the field has revealed the fact that although the key research questions for this line of research are obvious, foundations for model building are lacking. The existing frameworks have some similar, but also dissimilar steps. However, in the absence of a comprehensive theory, or at least a set of principles and modeling guidelines rooted in theory and empirical studies, all models look equally good, or equally poor, with very little basis to discriminate, and build confidence. Therefore, as a first fundamental step, this research focused on the possibility of improving the theoretical understanding of relation between character of organizations and their (system) safety output.

The first field that was reviewed for its potential use in safety models was simulation approach for organizations (see for example Carley, 2000, Carley & Lin, 1997). In such an approach, the focus is on modeling the organization as an information processor composed of a collection of intelligent individuals. Carley for instance assesses organizational adaptation using simulation software called ORGAHEAD. This software simulates the response to organizational changes, and the analysis of the results generates theoretical predictions on organizational adaptation. Research has shown that this approach of detail simulation has potential applicability in small organizations, but in large organizations loses its efficiency.

A totally different perspective can be seen in Biondi (1998), utilizing a conceptual model, named Complex Adaptive Non-Linear (CANL). The CANL model created by Bella (1997) is a qualitative representation of the migration process of a system towards its boundary. In Bella’s view, large organizations are complex systems, which adaptively change and self-organize. The non-linear response of organizations cannot be reduced to the intentions of the individuals that make it up. Their emergent outcomes can be found by the focus on the “whole” rather than “parts”. Bella believes that the global patterns of behavior that tend to reduce the safety of systems are common to all systems. They are: (1) “shift of the burden of proof”, (2) “productivity vs. safety conflicts”, (3) “work overload and time pressure”, and (4) "systemic distortion of information". These four global patterns of behavior are defined as "organizational factor type" by Biondi (1998). He states that the organization system can have an affect on the reliability through numerous interrelated ways (token). But, identification and classification of these tokens in detail are not possible. Biondi, instead, concentrated on organizational factors "type" instead of "token".

The idea of looking for "pattern of behavior" in organization is appealing, but the CANL approach is too qualitative to be linked to the quantitative risk models. Even the link proposed by Biondi's has not been discussed in detail. Searching for a more practical approach that could accommodate the concept of "pattern of behavior" in organization led to the *System Dynamics* literature. System dynamics (Forrester, 1957) is an extension of control theory/cybernetics to management. It is also applied to complex dynamic systems, involving psychological, social, technological or even environmental aspects (Sterman, 2000). System dynamics modeling can take into account nonlinear dynamics, feedback, time delays, and interdisciplinary aspects. System dynamics focuses on the pattern of system behavior (instead of events) based on time dependencies and dynamic behavior. They attempt to model the underlying structure of the system that creates a specific pattern of behavior.

Some references have used system dynamics modeling to describe the safety outcome of organization. For example, Cooke (2004) develops a system dynamics model of the Westray mine disaster. In his causal loop model of the accident, the interactions between safety and non-safety factors (e.g. productivity) are presented. Another example of utilizing system dynamics approach is STAMP developed by

Leveson (2004). In her point of view, safety can be shown as a control problem and managed by a control structure developed for a socio-technical system. In other words, Leveson tries to model the whole system from the control point of view.

Since event chain scenarios are capable of modeling technical risks (to be explained more in Chapter 4), it seems that framing the whole model as a control structure is not needed, and it makes the integrated model too complicated. A promising approach could be to model social aspects from control perspectives and link them to pre-existing PRA models, which have been able to develop technical system risk scenarios successfully. I found system dynamics as a powerful tool to model the pattern of organizational behavior, but without a comprehensive knowledge about the organizational behavior, system dynamics applications can be very misleading.

Studying a separate branch of management science, the *quality management* literature, I found that the idea of integrating safety and quality has been mentioned by some references such as Roughton, Lischeid, Peterson, Curis, Weinstein, and Manzella (Cooke, 2004). For example, Cooke (2004, p.91) proposed the idea of similarity between a risk system and a business system: "Just as we would apply quality management principles to control the quality of products and services from the business system, so we must apply similar principles to control the "quality" of incidents from the risk system." In his opinion, we could consider the incidents as quality problems. Organizations should apply an "incident learning system" to improve and analyze the deficiencies in risk systems in the same way they implement a "quality management system" to deal with quality problems and improve the business. A related terminology, named *Safety management*, has its root in quality management field. Safety management is defined as "the management process to achieve a state of freedom from unacceptable risks of harms" (Kennedy, R., Kirwan, B., 1998). Safety management is implemented via the organization's safety management system (SMS). It is referred to as a documented version of a safety management system and is carried out through established procedures, policies and regulations. It acts as a formal system of control over work activities and working methods, but it is not necessarily the way it exists in reality.

Many recent disasters happened not because of the way that safety was managed through the formal controls and procedures, but because of the *safety culture* in which safety management approaches were implemented (Kennedy, R., Kirwan, B., 1998). Safety culture is a sub-facet of *organizational culture* and is defined as common safety value in organization (e.g., Cooper, 2000, Cox & Cox, 1991).

Studying subjects such as organizational culture and climate, human resources systems, and more specifically safety culture and safety climate, and also organizational effectiveness model, I learned the concept of *configurational approach* in the organizational field. It was then, that I came across the interesting concept of "pattern" in the organizational field once more. Schulte et al. (2006, p.648) believe that configurations "allow for examining multiple characteristics simultaneously while accounting for the interrelationships and interactions among them". Configurational approaches have been applied to different areas of organizational research. The logic behind all these studies is the characterization of unit or organization based on “patterns” or “profiles” of different factors, instead of analyzing them independently.

After two and half years of multidisciplinary efforts, I started building the proposed organizational safety analysis framework, named Socio-Technical Risk Analysis (SoTeRiA[2]) , with the intention of improving existing accident theory (e.g. Reason’s model, 1990). This theory brings engineering, social, and behavioral science perspectives together under a modeling scheme, founded on relevant theories and observations. To my knowledge, no prior research has addressed these issues in a unified manner and on theoretical ground. Since the US Federal Aviation Administration (FAA) has sponsored my research, the proposed theory has been implemented in part in the aviation system. A hybrid modeling environment that is an integration of System Dynamics, Bayesian Belief Net (BBN), Event Sequence Diagram (ESD), and Fault Tree (FT) is proposed to operationalize the new theory. I believe this work extends the domain of complex systems modeling beyond the traditional scope, to also include, in a formal way, the human and organizational environments of the system in development and operation.

The remainder of this thesis is organized as follows (Figure 1.1). Chapter 2 provides a background by introducing the various fields and related literature that can flow into the field of organizational safety risk. We also discuss the open challenges that this research has sought to address.

Chapter 3, which is the first contribution of the current research, defines a set of principles that could guide the development of causal models for assessing the

[2] SoTeRiA was the goddess of safety, and of deliverance and preservation from harm in Greek mythology

impact of organizational factors on safety of technical systems. This includes the identification or development of a set of building blocks for causal models both in qualitative as well as quantitative terms. The impetus for this is the belief that methods and concepts that have evolved in a number of diverse disciplines can be adopted within an interdisciplinary framework, allowing a more comprehensive and more realistic coverage of the path of organizational influence on safety performance. The aim in Chapter 3 is to provide a brief summary of an overriding philosophy for building an organizational safety risk theory.

Chapter 4 provides a methodology for adapting appropriate modeling techniques, building proper interfaces, and creating a "hybrid" technique consistent with the principles described in Chapter 3. The described methodology is the second contribution of the current thesis.

Chapter 5 utilizes the findings described in Chapter 3 and 4 to propose a theoretical framework, named SoTeRiA, for quantitative organizational safety risk assessment. This is the third major contribution of the thesis. Chapter 6 demonstrates an example of applying the generic framework to Aviation Maintenance (the safety impact of maintenance activities as practiced in the commercial airlines). The final part, Chapter 7, concludes the thesis by summarizing the findings and outlining future extensions to the research. We also highlight which of the challenges addressed in Chapter 2, are answered in the current thesis.

The contents of Chapters 3, 4, and 5 point to the orientation of this research as theoretical rather than empirical. The *primary* objective is to develop a theoretically justifiable set of principles, on which a defensible framework can be built. Such principles are a series of testable propositions with supporting rationales, combination of past research, and/or integration of different theories across diverse disciplines. In some specific cases, expert judgment or plausible explanations are used to fill theoretical gaps.

The approach taken follows the general distinction that Whetten (1989) makes between theory development and empirical research and validation:

> "*During the theory-development processes, logic replaces data as the basis for evaluation. Theorists must convince others that their propositions make sense if they hope to have an impact on the practice of research. If the theoretical model is a useful guide for research, by definition, all the relationships in the model have not been tested. If all links have been empirically verified, the model is ready for the classroom and is of little value in the laboratory…The mission of a theory-development journal is to challenge and extent existing knowledge, not simply to rewrite it. Therefore, authors should push back the boundaries of our knowledge by providing compelling and logical justifications for altered views. This requires explaining the Whys underlying the reconstituted Whats and Hows. ....The primary difference between propositions and hypothesis is that propositions involve concepts, whereas hypothesis requires measures"*.

The principles and modeling framework developed in this research carry the characteristics articulated by Whetten (1989) for theory development. "What" and "how" are reflected in the framework. "What" refers to the elements of a framework and "how" is in the relations among the elements. "Why" explains the underlying rationale for the framework based on theoretical principles.

The *secondary* purpose of this thesis is to adapt appropriate quantitative tools to operationalize the theoretical framework. This is achieved by creating a hybrid modeling environment including deterministic and probabilistic methods. The current theoretically-based research can be followed by future studies that test the developed framework empirically in different contexts

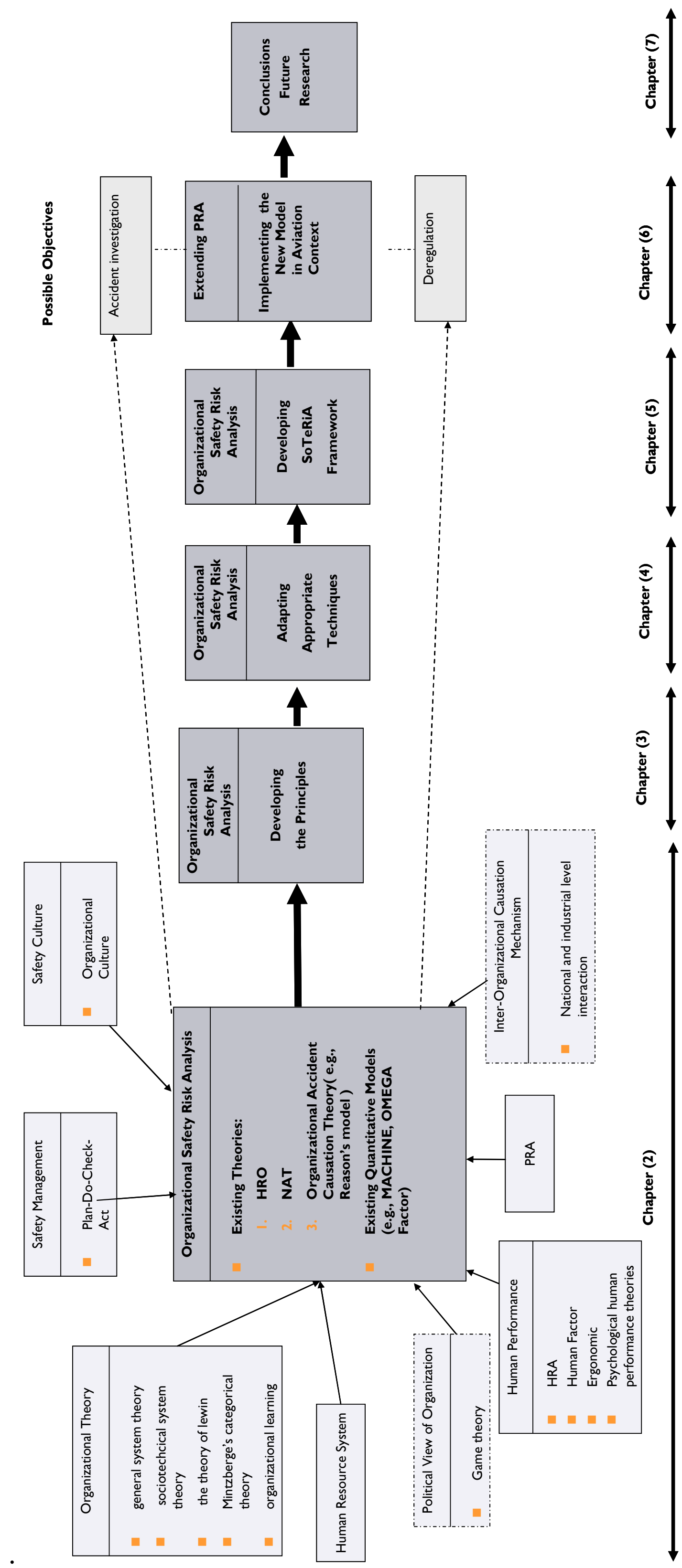

Figure 1.1 Research strategy outline

2. BACKGROUND

2.1 Introduction

This chapter serves as a background (the starting point in Figure1.1) for the remainder of the report. Section 2.2 describes the multidisciplinary nature of this field of research. Section 2.3 illustrates general trends in safety risk analysis. Section (2.4) introduces existing conceptual theories and quantitative frameworks in the field of organizational safety risk analysis. In Section (2.5), we discuss the open challenges that this research seeks to address. The related fields and corresponding literature are reviewed and summarized in Section (2.6).

2.2 The Multidisciplinary Nature of the Problem

The issue of safety risk management can be discussed from different points of view and in diverse disciplines. Rasmussen's (1997) view of the socio-technical system and relevant disciplines is depicted in Figure (2.1).

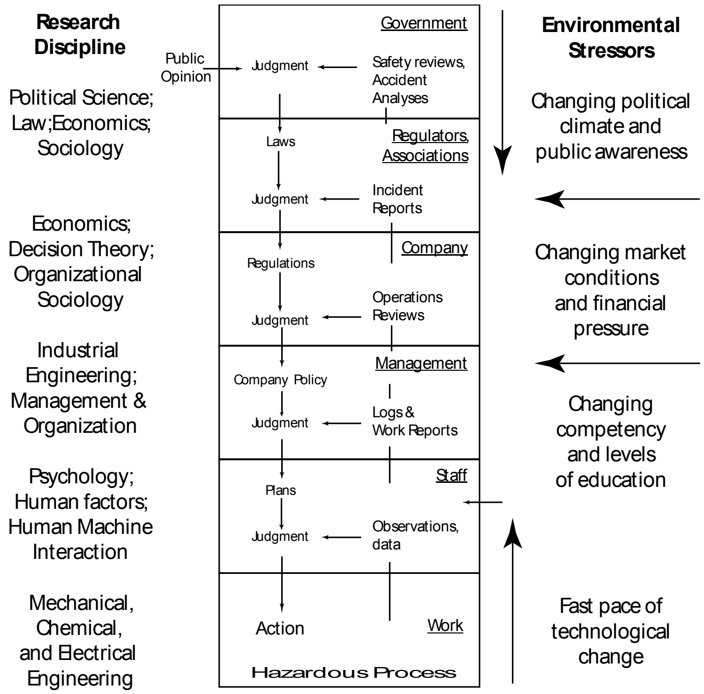

Figure 2.1 Different disciplines involved in risk management (Rasmussen, 1997)

At the top, society influences safety through regulations and the legal system. Legislation prioritizes the safety goals, a domain of interest to social and political scientists. The next levels concern the human and physical environments of the organizational in question, and that is the domain of management scientists, psychologists, as well as researchers in human–machine interactions, and engineers.

2.3 General Trends in Safety Risk Analysis

Over the past 25 years a significant improvement in the field of safety risk analysis can be observed. The nature of this improvement is in the shift from the first to the second and then to the third generation of models (Figure 2.2). This development has been in parallel to the shift in human sciences from normative, prescriptive models over to descriptive models, in terms of a deviation from rational performance, toward modeling the actual behavior. (Rasmussen, 1997)

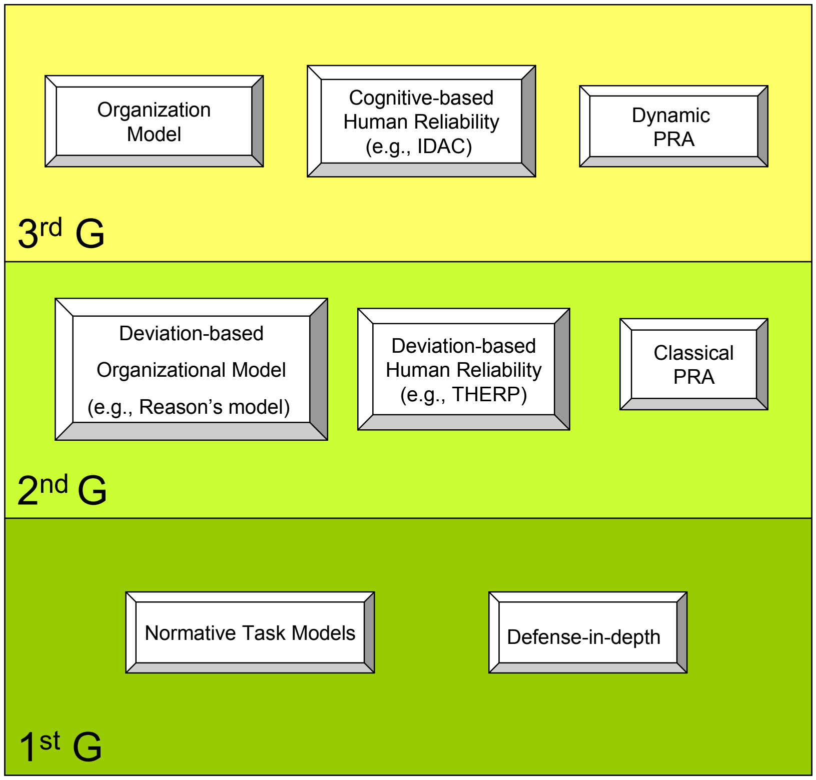

Figure 2.2 General Trends in Safety Risk Analysis

- First Generation (1950-1960): In this generation, high risk nuclear systems are designed on the basis of defense-in-depth protection (as in nuclear power systems), and multiple barriers (such as redundancies in modern aircraft). This philosophy led to very conservative designs and regulations in engineering systems with frequent quality control and inspection. Work instructions for operators and maintenance personnel were developed from the functional design. Formal standard operating procedures, developed by technical reliability analysis, were the only controlling tools for performance.

- Second Generation (1970-1990): This is the time that decision makers started using formal risk analysis (e.g. classical Probabilistic Risk Assessment (PRA)) covering primarily the technical system. Later, it was found that contributions to major accidents included "human error", in addition to technical failure. The first generation of human reliability methods, e.g. THERP (Technique for Human Error Rate Prediction), were developed to predict the probability that a given task procedure is accomplished successfully. Rasmussen (1997, p.207) calls this period a generation of "models in term of deviations from normative performance". Even the organizational accident model of this generation, such as Reason's model (1990), is based on "management errors" and deviations from "norm".
- Third Generation: In this generation, models moved toward presenting a more realistic performance of hardware, operators, and organizations. Classical PRA starts moving towards dynamic PRA. Operator models are becoming increasingly cognitive-based. These include CREAM (Cognitive Reliability and Error Analysis Method; Hollnagel, 1998) and IDAC (Information, Decision, and Action in Crew context), developed by Mosleh and Chang (2004). IDAC for example has a causal model of human behavior which is built based on cognitive theories rather than observable characteristics. Rasmussen called this phase a generation of "models in term of actual behavior" (1997, p. 208). In this generation, the modeling of "organizational accidents" is also moving toward representing the actual behavior. These include the methods to capture the dynamic nature of organizations (e.g. Cooke, 2004 & Leveson, 2003). However,

there are a number of major challenges in developing third-generation models in all three areas of organizational model, human reliability, and dynamic PRA. The research documented in this report is an attempt to improve the theoretical foundations of this generation of organizational safety risk analysis.

2.4 Existing Conceptual Theories & Quantitative Frameworks in the Field of Organizational Safety Risk Analysis

Existing studies in the field of organizational safety risk analysis are classified into three categories: (1) identification and classification of factors affecting organizational safety purposes, (2) conceptual theories, and (3) causal frameworks.

2.4.1 Classification of Organizational Factors for Safety Studies

Certain works on the organizational factors have been devoted mainly to the classification of such factors. The emphasis of some authors has been more on the completeness of the classifications than on their application in PRA. One example is the classification of Jacobs & Haber (1994):

- **Culture**
    (1) Organizational Culture
    (2) Ownership
    (3) Safety Culture
    (4) Time Urgency
- **Communication**
    (5) Communication-External
    (6) Communication-Interdepartmental

(7) Communication-Intradepartmental

- **Decision-making**

    (8) Centralization

    (9) Goal Prioritization

    (10) Organizational Learning

    (11) Resource Allocation

    (12) Problem Identification

- **Administrative knowledge**

    (13) Coordination of work

    (14) Formalization

    (15) Organizational Knowledge

    (16) Roles-Responsibilities

- **Human Resource administrative**

    (17) Performance Evaluation

    (18) Personnel selection

    (19) Technical Knowledge

    (20) Training

Other classifications have been used for safety evaluation of organizations. For example, Eisner (2003) provides a list of "safety matters" to map general management functions against safety- related issues in an organization. His purpose is to offer a method for an enterprise to evaluate its safety programs. Eisner's factors are classified into two groups of "program level" and "corporate level":

- **Program level Safety Elements**

Technology Elements

1. Process technology
2. Process Hazards Analysis
3. Operating Procedures and Safe Work Practices
4. Management of Change (Technology)

Personnel Elements

5. Training and Performance
6. Contractor safety and Performance
7. Management of Change (Personnel)
8. Incident Investigation and Communication
9. Emergency Planning and Response
10. Auditing

Facilities Elements

11. Quality Assurance
12. Mechanical Integrity
13. Pre-Start- up Safety Review
14. Management of “Subtle” change

- **Corporate Level safety Elements**

Safety Culture

1. Mission
2. Philosophy

3. Principles

Leadership and Commitment

4. Process Safety Management (PSM), Policies and Guidelines
5. Resource Commitment
6. Employee Involvement
7. Performance Accountability
8. Performance Verification

Operating Excellence

9. Open Communication
10. Teamwork
11. Common Shared Values
12. Do the Job the Right Way
13. Behavior Modification

2.4.2 Conceptual Theories

Based on Figure 2.2), organizational models appear in the second and third generation safety analyses. Thus, we classified the conceptual theories into second and third generation.

2.4.2.1 Second-generation Theories

Some accident causation theories mostly deal with occupational safety (e.g., Hale and Hale, 1972, Benner, 1975, Smillie and Ayoub, 1976). Many of these theories focus on "unsafe behavior" or "error" by individuals. Two major conceptualizations among these theories are: (1) event based modeling (Benner, 1995), and (2) energy flow modeling (Johnson, 1980). The first defines accident as "not a single event, but rather a transformation process by which a homeostatic activity is interpreted with accompanying unintentional harm. The critical point is that an accident is a process involving interacting elements and certain necessary or sufficient conditions". By contrast, according to the energy flow concept, an accident happens because of inadequate barriers. In other words, in this model the focus is barriers rather than processes, and accident is an "unwanted transfer of energy producing harm". Fahlbruch et al. (2000) rates these two models as best fundamental theories of accident.

In 1988, Peterson extended the accident causation theory from individual and local conditions to underlying management system. He proposed top managers are responsible for all accidents since they are in charge of designing, building, and/or operating the system.

Reason (1990) developed the concept of "organizational accidents" or "organizational error". As shown in Figure (2.2), we have classified his method among the second generation methods. Reason's "Swiss Cheese" model describes the contributing factors in an organizational accident (Figure 2.3), based on which, accidents happen because of defects in the elements involved in the organizational processes. These defects (failures) are pictured as "holes" within different layers of the system that change a production process to a failed process. The accident sequence starts with the failed or missing defenses in organization (that is, decisions concerned with planning, designing, managing, and communicating). These defects create latent conditions that are transmitted along organizational pathways to the supervisors (e.g., assignment of complex tasks to inexperienced technicians), and to their related departments, where they appear as conditions (such as high workload, time pressure, inadequate skills and experience, poor equipment, etc.) that cause errors or violations. At the level of individuals, these "local defects" (conditions) combine with psychological error tendencies to create the "unsafe acts". In other words, when the holes line up, the accident finally happens. (Figure 2.3)

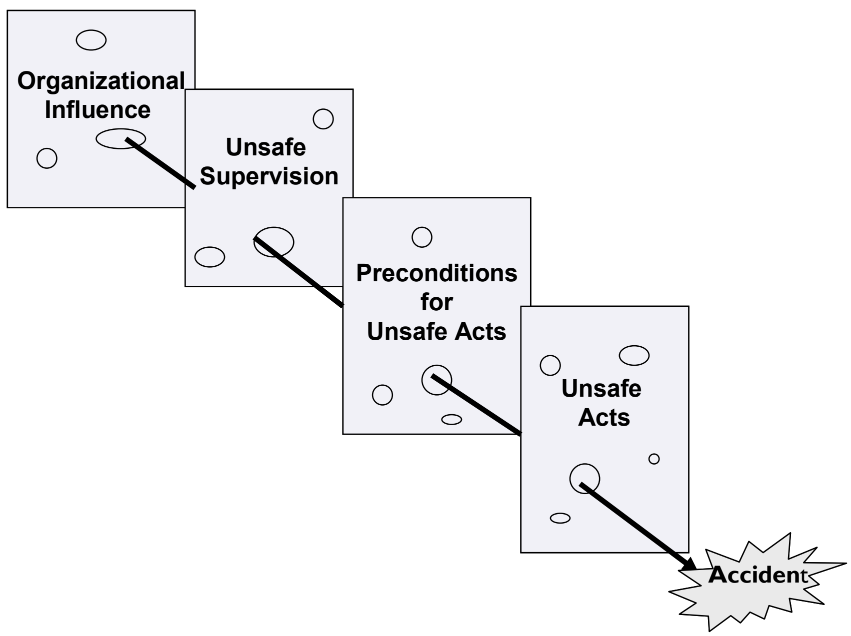

Figure 2.3 Reason's "Swiss Cheese" Model of Organizational Accident (Reason, 1990)

Later Groeneweg (1992) extended Reason's model to *Tripod Theory* with the philosophy of managing the "controllable aspects of human error" in the work environment. He defined eleven possible causes of errors, called "Basic Risk Factors (BRFs)", i.e. "design", "hardware", "maintenance", "housekeeping", "error enforcing conditions", "procedures", "training", "communication", "incompatible goal", "organization", and "defenses".

2.4.2.1 Third-generation Theories

The third-generation organizational accident theories focus mostly on systematic and collective nature of organization error, rather than decomposing it to a chain of errors. The concept of a "natural migration of activities" toward the boundary of acceptable performance has been developed by Rasmussen (1997). He emphasizes that for risk management, we need to find the underlying mechanism of migration. He believes every workplace is bounded by administrative, functional, and safety related constraints. Objectives and constraints shape individual behaviors. People adapt to these constraints or change some of them to better suit their goals. During these adaptive processes, management supplies an effective "cost gradient" and workers try to find an "effort gradient". The result of these two gradients will be the system migration towards the boundaries. The accidents might occur if the system crosses these boundaries.

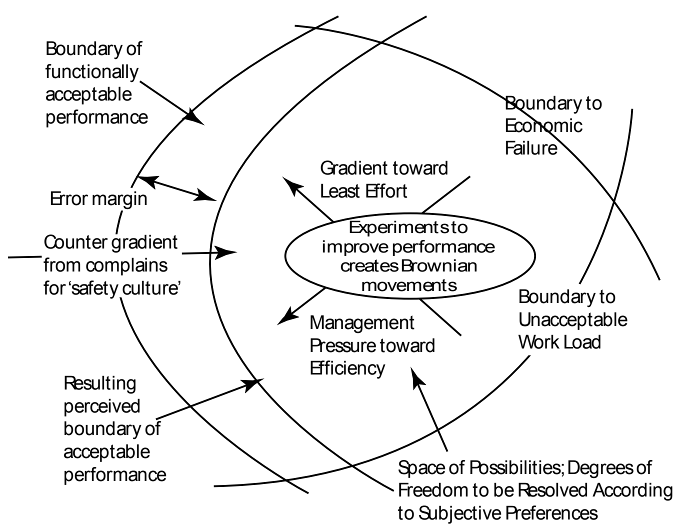

Figure 2.4 Natural migration of activities towards boundaries (Rasmussen, 1997)

It’s important to understand that when the system is close to the safety boundaries, any act of individual that might be considered as “normal” in normal situations could be critical and become the root cause of the accident. Even if this specific root cause is avoided by additional safety activities, it might be initiated by another cause. Therefore, new methods of risk management should focus on the mechanisms “generating behavior in actual dynamic work context” to prevent the system from approaching its safety boundaries (Rasmussen, 1997). (see Figure 2.4)

Normal Accident Theory, developed by Perrow (1984), views accidents as inevitable in complex socio-technical systems. The two characteristics of these systems are “interactive complexity” and “tight-coupling”. The most important measure of “interactive complexity” is the number of variables in the system and their relationships as well as the number of feedbacks loops. The measure of coupling is the pace that changes in one variable will affect the changes in other variables. Based on this theory, due to interactive complexity and close coupling, some of the changes in organizations are unpredictable, and potentially lead to disasters. Another camp of expert disagree and point out a number of high hazard organizations that have not had any accidents for decades. This discussion has led to the study of organizational success rather than failure, and the concept of “*High Reliability Organizations*” (HROs). According to Weick and Sutcliffe (2001) and Roberts and Bea (2001), serious accidents can be prevented by properly managed organizational processes and practices.

Both normal accident theory and high reliability theory are holistic in nature, therefore it is hard to prove or disprove. These two represent the extreme possible cases, with reality most likely somewhere in between.

2.4.3 Quantitative Frameworks

There are a number of quantitative methods and frameworks that aim at quantifying the impact of organizational factors of safety risk. Most of the existing quantitative frameworks such as MACHINE (Embrey, 1992), WPAM (Davoudian, 1994), , SAM (Pate-Cornell, 1996), Omega Factor Model (Mosleh, 1999), ASRM (Luxhoj, 2004), and "Causal Modeling of Air Safety" (Roelen et al., 2003), are essentially second generation methods. The majority of these include the three key parts: organization model, operator model, and technical system model. Their commonalties and shortcomings are described in Section (2.4.3.1).

Third-generation frameworks are still in development phase. Among these, we can name Cooke (2004), Leveson(2003), and Mousang (2004). These models have not been yet expanded adequately to include the third-generation human behavior models and third-generation technical systems risk models. Section (2.4.3.2) reviews third-generation models. Section (2.4.3.3) highlights some open questions in this field of research, some of which are targeted to be answered in this report.

2.4.3.1 Second-generation

All second generation models are more or less composed of the following parts:

(1) A set of organizational factors:

Most models (e.g., MACHINE (Embrey, 1992)), have developed their factors based on *accident data*. MACHINE, which has been used to analyze railway accidents in the United Kingdom, views accident causation as a process involving three levels: Level 1 includes latent, active, and recovery errors; Level 2 includes error-inducing factors such as training, procedures, time pressure, responsibilities, etc.; and Level 3 includes policy deficiencies such as project management, safety culture, training policy, etc.

Some of these frameworks have used a *predefined* set of factors. For example, WPAM (Davoudian et al. 1994a and 1994b) uses a set of 20 organizational factors developed for Nuclear Regulatory Commission (Jacobs & Haber, 1994). WPAM has three levels. The top level is an event tree that ends in a critical accident. The other two levels are organizational factors; the first one is the overall culture (communication, decision making, etc.), and the second level includes certain attributes of decision making, communication, etc.

The set of factors in some frameworks is based on certain *specific theories*. For example, SAM (Pate-Cornell, 1996) describes the organization as a set of decisions and uses four different theories for different kinds of decisions. Three models represent the actor's intention: a rule-based decision model for rule-based decisions, both a rational and a bounded rational model for knowledge-based decisions, and one related to the actual execution for skill–based actions. The selection of relevant organizational factors depends on which of the four explicit models can describe a given decision.

As another example, Roelen et al. (2002& 2003) present a causal model for aviation systems. The structure of their management model is based on safety management systems (SMS). The set of organizational factors in this model include generic "delivery systems" in SMS. SMS is characterized as a control process with three levels: (1) Execution, (2) Plans and Procedures, and (3) Structure and Policy. SMS must manage the delivery of "resources" and "criteria" to the right place and at the right time for the execution level. "Resources" are people, hardware, money, time, and information that are needed for a task to be done. The "criteria" are the procedures that direct people in performing the tasks, and standards according to which they need to adhere. Roelen et al. define several generic categories of delivery systems including "Competence", "Availability", "Commitment", "Man-Machine Interface", "Communication", "Plans", "Conflict Resolution", "Spares and Tools", and "Change Management".

The Omega Factor approach (Mosleh & Golfeiz, 1999) represents an organization by a *model* not just a set of factors. An organization model is a descriptive and/or predictive representation of the way the organization affects the performance of its workers and work products. The model considers both the structural as well as the behavioral aspects of the organization. Structural aspects refer to (1) organization positions (e.g., general manager, unit manager, maintenance worker, etc.) and (2) organization divisions, groups, work units, etc. In contrast, behavioral aspects refer to (1) people's responsibilities (e.g., formal job specifications), (2) objectives, performance measures, and products of the organization, or its divisions, units, groups, etc., (3) means and processes used for production and achieving objectives, and (4) attributes and characteristics of the above. This model of an organization recognizes the relationships between these elements. The relationship could be implicit (e.g., relative position of an element in the model, e.g., supremacy of manager over the worker in the hierarchy of the organization), or explicit (e.g., dependence of a worker in performing his or her job on the availability of tools and quality of training). But the approach for the construction of the model is heavily focused on formal relationships, effectively disregarding the very important informal network.

Another approach, ASRM (Luxhoj, et al., 2001), utilizes Human Factors Analysis and Classification System (HFACS). HFAC was developed by Weigmann and Shappell (2000) based on Reason's model, and in the context of aviation. ASRM includes organizational influence (resource management, organizational climate, and organizational processes), preconditions for unsafe acts (adverse mental states, adverse physiological states, physical /mental limitations, crew resources management, and personal readiness), and individual unsafe acts (decision errors, skill-based errors, perceptual errors, routine violations, and exceptional violations). Luxhoj et al. use expert knowledge to build the detail path of causalities among the factors.

<u>(2) A link to the risk model</u>

In SAM (Murphy and Pate-Cornell, 1996), the link between the management model and the risk model is the individuals' decision and actions. A commentary point on SAM is that decisions and actions by individuals tend to be shaped by reinforcing patterns of systematic behavior, rather than rational decisions and written objectives and policies established by the top managers. The climate and culture in which the decisions are made do influence the decisions.

The Omega factor model creates a relation between organization performance and hardware failure with the help of a parameter called omega, which is the ratio of component rate of failure due to organizational factors to its “inherent" failure rate. The inherent portion of the failure rate represents failure mechanisms which are beyond the control of the organization in charge of operating the system. The value of the ω-factor is caries the quantitative influence of organizational factors on component failure probabilities, and through them the system risk.

In WPAM (Davoudian et.al, 1994a and 1994b), the link is established through work process model. In this model, task analysis of each key work process is conducted, and an organizational-factor (OF) event tree for each key work process is constructed. The human reliability model and the detailed path of influence of organizational factors are not modeled in WPAM. WPAM concentrates on capturing the "common-cause" effect of organizational factors on system risk. It considers organizational common-cause effects on similar and dissimilar systems. It includes a category of causes that synchronize failures of multiple components so that failures happen simultaneously or within a short period of time. For example, use of the same erroneous procedure for maintenance of a component can simultaneously cause failure of all components subjected to that specific maintenance. But, as Mosleh and Golfeiz (1999) point out, the dependency of organizational factors is not always of the above form. There is another class of failure mechanisms where a single underlying cause increases the failure rate of multiple components. This results in a shorter time between failures, but each component fails conditionally independently and that times of failure are still random and independent. This is a different mechanism of dependence as compared with the type considered in conventional CCF analyses.

Some models such as MACHINE (Embrey, 1992) and ASRM (Luxhoj, 2001) use a human model as a link. Using a human reliability model is important, especially for the cases where human behavior and decisions are the critical factors in system risk. In Roeln's model (2002, 2003), safety critical tasks are the link to the technical system accident risk model. For example, all maintenance activities are specified as safety critical tasks. The processes that are carried out within the aviation system are analyzed and broken down into tasks and subtasks using Hierarchical Task Analysis.

<u>(3) A Set of Modeling Techniques</u>

Most of the above methods use variations of Bayesian Belief Network (BBN) or Influence Diagram. This modeling technique is explained in Chapter 4. In MACHINE, between each level (level 1, 2, and 3) there is a many to many pattern of influences that has been implemented using Influence Diagram. In the Omega factor, the result of the quantification of influence diagrams is a parameter, P, which is the degree (or probability) that the organization product (e.g., worker's performance) is adversely affected by the relevant organizational factors. A variety of ways to model the relationship between ω and P are established. In SAM, the Influence Diagram connects a chain of conditional probabilities. WPAM utilizes flow diagrams to relate work processes and organizational factors. A similar technique, named process modeling technique, is explained in Section (4.4).

<u>(4) A set of Measurement Methods</u>

None of the existing quantitative safety frameworks adequately discusses the methods of measuring their factors. Some have exclusively relied on expert judgment (e.g., Embrey (1992)) for measurement. WPAM (Davoudian et al, 1994) suggest surveys, behavioral checklist, and interview as well as expert judgment. These measurement methods are mainly the ones suggested by Jacobs and Haber (1994) for their 20 organizational factors for the nuclear power industry. Others have used a combination of expert and historical data (e.g., Omega factor (Mosleh & Golfeiz, 1999), ASRM (Luxhoj, 2001)). Murphy and Pate-Cornell (1996) partially relied on theories as basis for measurements. In their earlier work, expert judgment is used for the measurement of the conditional probabilities. But in the developed SAM framework, the link between management factors and human action is based on organizational theory through the four human behavioral models mentioned before. In this case the quantification of the links is based on their related theories.

2.4.3.2 Third-generation Models

Third-generation models intend to picture the actual performance of organization, rather than the concept of deviation from normative performance. The existing third-generation organizational safety frameworks mostly tackle the dynamic aspects of organizational influences. For example, Biondi (1998) has used the qualitative model developed by Bella (1997) to describe the changes in the reliability of a system due to organizational dynamics. Bella' model (1997) is a qualitative representation of the migration process of a system towards its safety boundary.

In Bella's opinion, large organizations are complex systems, which adaptively change and self-organize. Their non-linear response can not be reduced to the intentions of the members of the organization. Their emergent outcomes can be understood by focusing on the "whole" rather than the "parts". CANL model can explain the non-linear organic responses and their evolution over time. According to Bella, CANL model can be applied to an organization through a "search for behavioral loops". Loop diagrams represent the qualitative causal relationships within the system. Bella believes that the global patterns of behavior that tend to reduce the safety of the technological systems are common to different systems. These are: (1) "shift of the burden of the poof", (2) "productivity vs. safety conflicts", (3) "work overload and time pressure", and (4) "systemic distortion of information".

Bella's four global patterns of behavior are defined as "organizational factor types" by Biondi (1998). Organizational factors are a set of conditions that provide context for human behavior (actions and decisions). They are emergent outcome of dynamic interactions of the members of an organization. According to Biondi an organization can affect reliability through countless interrelated ways (token). Therefore, identification and classification of these tokens in detail are not possible. Biondi concentrates on organizational factor "type" instead of "token". He believes that all such organizational factors types have a common "Organizational Root Factor", which is "systemic imbalance". Systemic imbalance changes the flow of information and resources in the organization and causes the failure. He uses the

CANL model to measure the "reliability state" of organizations. The reliability state of an organization is the degree of systemic imbalance, or the measure of its organizational factor types. The measure is based on an interpretation of loops that reinforce unsafe actions.

Some other references have used system dynamics modeling (e.g., Sterman, 2000) to describe the dynamics of an organization. For example, Cooke (2004) developed a system dynamics model of the Westray mine disaster. In his causal loop model of the accident, the interactions between safety and non-safety factors (e.g. productivity) are presented. Based on the simulation model of the Westray mine disaster, he made the following observations: (1) rapid increase of the incident rate, resulting from placing higher priority on production over safety, (2) criticality of management commitment to safety for controlling the risky scenarios, (3) accidents are the consequence of the system as a "whole" rather than individual components, and (4) change in safety culture as measured by management and personnel safety commitment has a large time delays.

Another example of utilizing system dynamics approach for safety is the Systems-Theoretic Accident Model and Processes (STAMP) model, developed by Leveson (2004). In her view, safety can be shown as a control problem and managed by a control structure developed for a socio-technical system. In other words, Leveson tries to model the whole system from the control point of view. A system in her conceptualization is not a static design, but a dynamic process that is continually adapting (changing to fit into a new occasion) to achieve its objective. Since the system is changing over time, the safety (control) system is a continuous task to enforce the necessary constraints in order to provide safe adaptation. Accidents can be studied in this model, identifying which safety constraints were ignored or violated and why the controls imposed were insufficient.

Since event chain scenarios are capable of modeling technical risks (to be explained more in the Chapter 4), it seems that framing the whole model as a control structure is not needed, and it makes the integrated model too complicated. A promising approach could be to model social aspects from control perspectives and link them to existing PRA models, which have been able to develop technical system risk scenarios successfully.

Yu et al. (2004) also used system dynamics modeling in the context of nuclear power plants to assess the effects of organizational factors on plant safety. They conclude that system dynamics technique can effectively facilitate dealing with interactions and dependencies among the organizational factors. Their work is an attempt to link system dynamics and PRA. However, the interconnection between PRA and system dynamics is not clarified. Besides, they do not provide sufficient theoretical support for their proposed organizational model.

2.5 Open Challenges

As we mentioned in Section (2.3), the field of safety risk analysis is gradually moving from the second-generation toward the third-generation methods. (see Figure 2.2) The transitions involved in the development of third-generation organizational safety frameworks and their related research area, are depicted in Figure (2.5). As the review of second generation frameworks show, the majority include three key parts:

“organization model” (A), “human model” (B), and “technical system model” (C). In contrast, third-generation frameworks are still in early stages of development, and only few models can be identified as organization models (D). These models have not been yet expanded effectively to include the third-generation “human model (E), and the third-generation “technical system models” (F).

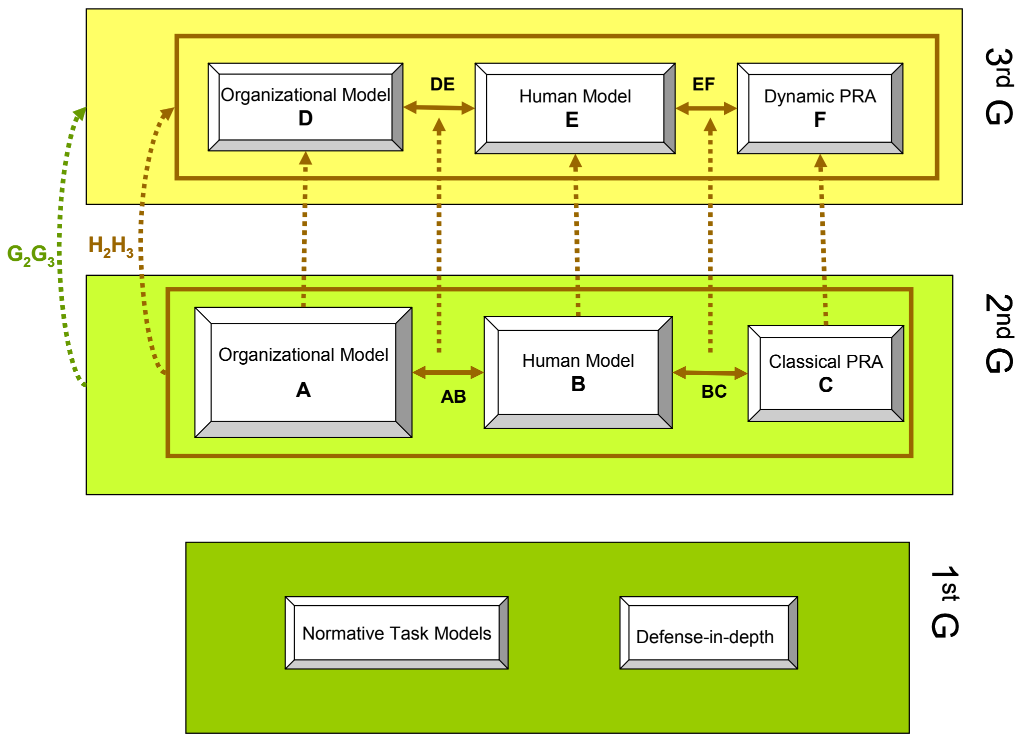

Figure 2.5 The research area for developing third-generation organizational safety frameworks

The dotted arrows in Figure (2.5) illustrate the challenges of moving from second to third-generation frameworks. The followings are a number of open questions associated with each of the above mentioned research areas:

$\underline{H_2H_3}$

- Do we need to have three parts, i.e. technical, organizational, and individual models in the third-generation organizational safety formwork? If so, why?
- Which modeling environment can accommodate and cover all three parts together?
- How can we evaluate the organizational safety frameworks?

$\underline{G_2G_3}$

- What are the underlying differences between the third- and the second-generation methods?

$\underline{A \rightarrow D}$

- Which fields/literature should be searched for constructing the organizational part of third-generation safety frameworks?
- What should be the elements of D? What elements are missing in the second- generation models? Which elements of second-generation models can be modified or generalized for use in the third-generation models?
- What is the underlying theory (or theories) for establishing the causal relation between the factors of the organization model?
- How can we adequately account for interactions and dependencies among the factors?
- What would be the best technique to "operationalize" the organizational safety frameworks?
- How should we measure the factors or elements of the safety model? What is the best measurement approach for safety frameworks?

- How should we consider the interaction of safety and other organizational performance measures (such as financial performance)?
- How should we account for the dynamic aspects of organizational safety behavior? (Comment: one of the challenges of second-generation models are their deficiency in modeling the dynamic behavior of an organization including the impact of change during a transition, the delay between causes and effects, the time order of events e.g., decision/actions, and feedback loops).
- How can we relate the inter-organizational effects on the safety performances?

<u>AB→DE</u>

- How should we connect the organization model to the human performance model?
- Can we generalize the links used in second generation models to the third generation?

<u>B→E</u>

- How should the third-generation human performance models be built?
- Which aspects of second-generation human models can be generalized for the third-generation?
- What technique can handle the high interaction and dependency of the individual-level factors?

- How we can deal with dynamics at the individual-level?
- What would be the individual level-factors?

<u>BC→EF</u>

- How should we connect the human model to the technical part?
- Can we generalize the link in the second generation to the third?

<u>C→F</u>

- Where would be the place of technical system model in an organizational safety framework? (comment: this is the only question that is covered in the current report in relation to C→F)
- How we can go from second-generation PRA (technical system) to the third generation?
- What would be the best modeling technique for the third-generation technical system?

The remainder of this report investigates answers to a subset of these questions. Some categories (nearly all of CF and parts of BE) are out of the scope of the current research. In the final chapter of this report we make an assessment of the extent to which these questions are answered.

2.6 The Related Fields

The disciplines that can feed into the immature field of Organizational Safety Risk analysis are explored. They mainly consist of safety management, safety culture, organizational theory, human resource system, human reliability, and PRA. Clearly, these are not mutually exclusive fields or literature. There are overlaps, and often the differences on common subjects stem from their different perspectives. The following is a brief summary of the relevant fields. Much of the relevant literature used in support of the argument and ideas of report, however, are cited throughout the report to support the specific positions taken or to contrast the techniques introduced.

2.6.1 Technical System Risk

The primary and most popular set of methods for technical system risk assessment is known as *Probabilistic Risk Assessment (PRA)*. The roots of PRA methods can be traced to the reliability and safety assessments in the U.S. aerospace and missile programs in the 1960s. Later, in the 70's and 80's the nuclear industry extended PRA methods for identifying and assessing risks of commercial nuclear power plants. The analytical techniques were gradually improved and applied over the next two decades, not only in the nuclear industry, but also in other fields such as the offshore oil, petrochemical, and defense industries.

The NASA PRA Guide (Stamatelatos , 2002) describes eleven procedural elements for PRA, including objectives and methodology definition, familiarization and information assembly, identification of initiating events, sequence or scenario development logic modeling, failure data collection and analysis, quantification and integration, uncertainty analysis, sensitivity analysis, risk ranking, and interpretation of the results. In Section (4.2), we briefly describe some of the key techniques of classical PRA such as Fault Tree and Event Sequence Diagram.

2.6.2 Human Safety Performance Model

Human errors are present in all phases of system life (planning/design, construction, operation, maintenance, and management) and account for 30%-90% of all causes of industrial accidents. Human Reliability Analysis (HRA), which is the study of the nature, causes, and probability of human actions in the design and operation of systems and processes, emerged out of need to provide an assessment of human error probability in PRAs. Mosleh & Chang (2004a) describe Human Reliability as a methodology, a theoretical concept, and a measurement method. As a methodology, it is a procedure for conducting a quantitative analysis to predict the likelihood of human error; as a theoretical concept, it develops an explanation of human errors in technical systems; and as a measure, human reliability is the probability of successful performance of a task by an individual.

Some other disciplines such as Human Factors, Human Engineering, Ergonomics (see Wickens & Gordon, 1997), and Engineering Psychology (see Wickens & Hollands, 2000) are relevant to HRA. In Human Factors and Ergonomics the emphasis is on equipment design to maximize productivity by reducing operator discomfort and fatigue and to meet the requirements of human operators. The emphasis of Engineering Psychology is on understanding the human mind to identify human limitations and capabilities as part of system design. In contrast, the emphasis of Human Reliability lies on estimating Human Error Probability (HEP).

Over the past 20 years, more than 40 methods of HRA have been developed. These methods are classified into *first-generation* methods, such as THERP (Technique for Human Error Rate Prediction; Swain, 1983), SLIM-MAUD (Success

Likelihood Index Method- Multi-attribute Utility Decomposition ; Embrey et al., 1984), HCR (Human Cognitive Reliability Model; Spurgin et al, 1990) , NARA (Nuclear Action Reliability Assessment; Kirwin et al., 2004) , and *second-generation* such as CREAM (Cognitive Reliability and Error Analysis Method; Hollnagel, 1998), ATHENA (A Technique for Human Event Analysis; Barriere et al. , 2000), and IDAC (Information, Diagnosis & Decision, Action in Crew Context; Mosleh & Chang, 2004 b). The first generation methods mainly cover Errors of Omission (EOO). These methods do not provide any causal picture of operator error, and the error probability is mainly estimated on the basis of a set of performance shaping factors (PSFs). In contrast, the second-generation methods take into account the context of operators' cognitive decisions. These methods attempt to cover Error of Commission (EOC) in addition to EOO.

Figure (2.6) shows an example of the types of factors that are considered in second and third generation HRA methods. This figure is from the IDAC approach where an operator interacts with the external world (i.e., other operators, the system, the external resources) to achieve a set of goals (e.g., recover a failed engine). The operator's problem-solving process is influenced by factors that are internal or external to the operator. The internal influencing factors cover the operator's psychological, cognitive, and physical states. The external influencing factors include team-related factors, organizational factors. The external factors must be perceived by the operator to influence the operator's error. The internal and external influencing factors are collectively labeled as performance influencing factors (PIF). (Figure 2.6)

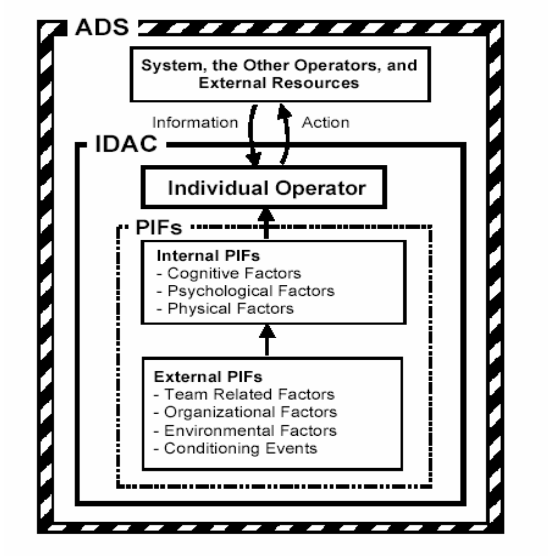

Figure 2.6 External and internal PIF in IDAC model (Mosleh & Chang, 2004b)

The main focus of the present report is modeling organizational factors among the external PIFs.

2.6.3 Organization Performance Model

The first field that was reviewed for its potential use in safety models was a *simulation* approach to organizations (see for example Carley (2000)). In this approach, the focus is on modeling the organization as an information processor composed of a collection of intelligent individuals. Carley, for instance, assesses organizational adaptation using simulation software called ORGAHEAD. This software simulates the response to organizational changes, and the analysis of the results generates theoretical predictions on organizational adaptation. Research has shown that this approach (detail simulation) has potential applicability in small organizations, but in large organizations it loses its effectiveness.

Review of organizational literature revealed two different lines of research. (see Figure 2.7) The focus of one is quality management, and the related term, safety management. Another line has a psychological orientation and studies culture and climate, and related terms safety culture and safety climate. Some researchers have studied connections between the quality management view of organizations and organizational performance. For example, Good (1999) attempts to link Total Quality Management (TQM) to financial performance and Ichniowski & Shaw (1999) study the relation between the quality of human resource system and economic performance of organizations. Similarly, some other researchers have tried to link safety management to safety performances. For example, Mc Donald et al. (2000) have shown a relation between safety management and safety outcomes.

Other studies focus on the relations between culture/climate and organizational performances. For example, the effect of culture on financial performance is studied by Siehl and Martin (1990). Lin, Madu, & Kuei (1999) have linked global climate dimensions to quality management outcomes. Also, Zohar (2000) has explored the relation between group-level safety climate and objectively measured number of injuries. In another study, Vurren (2000) has shown a relation between safety culture and incident causation in organization.

Another group of studies discusses the relation between organizational performance (e.g., quality, financial state) and safety. For example, D. Golbe (1986) has studied the relationship between profitability and safety in airlines.

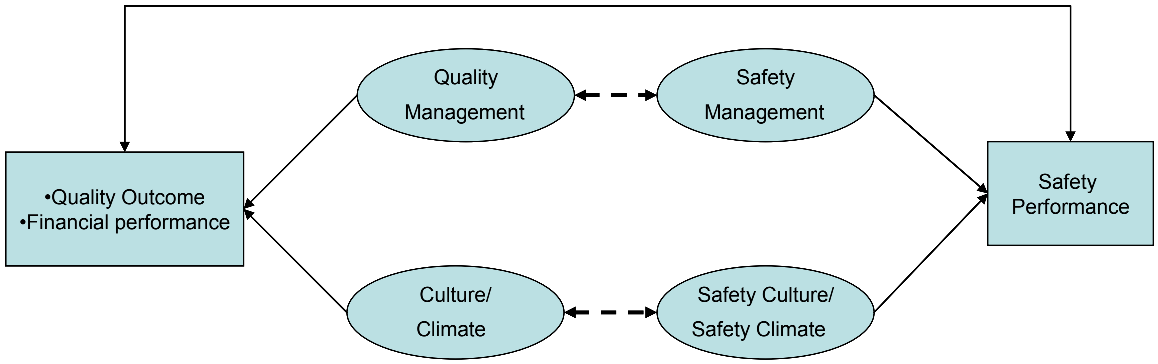

Figure 2.7 Relation of various literatures on quality, culture/climate, and safety

In reviewing the *quality management* literature, it was found that the idea of integrating safety and quality has been mentioned by some references such as Roughton, Lischeid, Peterson, Curis, Weinstein, and Manzella (Cooke, 2004). For example, Cooke (2004, p.91) proposed the idea of similarity between a risk system and a business system: "Just as we would apply quality management principles to control the quality of products and services from the business system, so we must apply similar principles to control the "quality" of incidents from the risk system." In his opinion, we could consider safety incidents as quality problems. Organizations should apply an "incident learning system" to improve and analyze the deficiencies in risk systems in the same way they implement a "quality management system" to deal with quality problems and progress the business. As defects are the visible expressions of poor quality management, the visible representations of poor risk management are the incidents that are produced by a system during normal operation. System risk arises from the characteristics of operation (e.g. the transformation process, the operation and maintenance procedures, and interactions of people and technology in the operation). This is similar to the creation of performance quality through the characteristics of products and services.

A related terminology, *Safety Management,* has its root in the quality management field and the “plan-do-check-act” cycle of Deming (1990). Safety management is defined as “the management process to achieve a state of freedom from unacceptable risks of harms” (Kennedy, R., Kirwan, B., 1998). Safety management is implemented via the organization’s safety management system (SMS). It is referred to as a documented version of a safety management system, carried out through established procedures, policies and regulations. It acts as a formal system of control over work activities and working methods. We refer the reader to Hale et al. (1997) and Hale & Braram (1998) for more detailed review of safety management concepts.

The British Standard BS 8800 (1996), describes links between safety management activities, ISO 9001 quality standard, and ISO 14001 environmental management standard. Since mid-1990s, the central management trends have been moving towards developing a comprehensive management system that includes both the improvement of products and the internal activities. Malcolm Baldrige National Quality Awards (MBNQA) and the European Foundation for Quality Management (EFQM) Excellence model are examples of this trend. Although quality is focused on the customer’s needs, the business philosophy of MBNQA winners in the service industries is People-Service- Profits (P-S-P), with the view that providing a quality working environment for employees leads to quality service, and that is what ultimately leads to profits. (American Management Association 1997) A quality management framework for risk control would be a very important view, because risk management like quality management needs an integrated socio-technical approach to include employee involvement, technical systems, and management practices.

Many recent disasters happened not because of the way that safety was managed through the formal controls and procedures, but because of the *safety culture* in which safety management approaches were implemented (Kennedy, R., Kirwan, B., 1998). Safety culture is a sub-facet of *organizational culture* and is defined as the common safety value in organization (e.g., Cooper, 2000, Cox & Cox, 1991). Likewise, *safety climate* is a sub-facet of *organizational climate* and is expressed as the shared perception of employees regarding organizational safety practices (e.g., Zohar & Luria, 2005, Griffin & Neal, 2000). In Section (4.9) we will explain safety culture and climate in more detail.

Another related research line is *trade-off analysis* for strategic safety decisions. It concentrates on optimization of the managerial decisions, from the standpoint of safety and productivity. Baron & Pate-Cornel (1999) believe that managers face a trade-off between productivity and safety in a changing business environment. Pate-Cornel has studied this aspect in context of cost benefit analysis regarding maintenance.

There are some other fields that served as background to this research, but have not been discussed in this writing. They include certain theories/models from *organizational theory* field, such as socio-technical system theory (Emery & Trist, 1960), Lewinian filed theory (Lewin, 1951), Mintzberg categorical theory (1983), and organizational performance and change models (e.g., Burke & Litwin 1992), as well as theories of learning organization (e.g., Senge, 1990). Also, we have not expanded this chapter to the review of the *human resource system* (e.g., Ostroff, 1995), which is the collection of organizational practices that support individuals' performance in organizations including the people who have influence on or conduct the safety critical tasks.

Two aspects that are not explored deeply in this report are the *political view* of organizations and *inter-organizational* causation mechanisms. Based on Bolman and Deal (1984), one of the frames of an organization is the political view that considers an organization as a coalition between groups with different values. The decisions in organizations are viewed as a way to allocate scarce resources, and theories such as game theory are utilized to model them. Another important aspect is the study of inter-organizational effects. Although we have considered the effects of some regulatory practices, such as the regulatory auditing system, and the indirect effects of regulation through some standards and codes, we have not studied regulation and policies at the national and industry level. The other three aspects of Bolman framework, Structural, Human resource, and Symbolic, have been tackled in building the organizational safety framework presented in this report.

3. ORGANIZATIONAL SAFETY RISK ANALYSIS: PRINCIPLES

3.1 Introduction

This chapter elaborates upon the first contribution of our research: identifying theoretical principles to guide the development and evaluation of organizational safety risk frameworks. The impetus for this is the notion that methods and concepts that have evolved in a number of diverse disciplines can be adopted within an interdisciplinary framework that allows a more comprehensive and more realistic coverage of the path of organizational influence on safety performance.

What is described here provides insights into possible theoretical foundations and principles for the field of "Organizational Safety Risk Analysis". Since exploring such foundations spans diverse disciplines such as risk analysis, industrial/organizational psychology, organizational theory, and human reliability, it is anticipated that the unstated concepts, principles, and assumptions in this field would be obvious to the members of one discipline, but not others. The issues discussed, however, are central to the development of organizational safety analysis theories and provide conceptual guidance for theorists seeking to develop integrated safety frameworks for specific industries and organizations, specific safety outputs (e.g. large scale accidents, occupational hazards, and information system security), and specific phases of interest (e.g., operation and design).

In order to explore these principles, theory development studies, especially organizational theory development studies (e.g. Dubin, 1978, Whetten, 1989, Bacharach, 1989, and Kozlowski & Klein, 2000) are reviewed and adapted for safety risk analysis. Bacharach (1989, p.496) defines theory as "a statement of the relation among concepts within a set of boundary assumptions and constraints". He states that two important functions of a theoretical statement are to "organize" and to "communicate". The development of this chapter, as in similar efforts, aim at identifying the key building blocks, criteria, and rules of a theory that would accomplish these two functions.

We will first describe the background, specific issue or question, or the identified need, and then end with the statement of the resulting principle. The principles are stated at the highest possible end of abstraction that would give the principles their broadest reach and applicability irrespective of the particular selected modeling approach.

3.2 Designation & Definition of the Objective

3.2.1 Defining the Unknown of Interest

Development of a theory should start with identifying and defining the "unknown of interest" otherwise known as "dependent variable" for the theory. It leads to finding the level of analysis (Section 3.3), constructing factors (Section 3.4), and the linking mechanisms (Section 3.5) to be developed by theory.

PRINCIPLE (A)

Organizational Safety Risk (OSR) is the unknown of interest for Organizational Safety Risk Theory, and is a measure of the safety performance of the whole, or some sub-units of the organization. Formally

$$OSR = f(F_1, F_2, \ldots, F_N)$$

where f stands for an explicit or implicit function , and F_1 , F_2 , …, F_N *are the predictors (independent variables).*

Risk is a construct of two key notions: "uncertainty" and "undesirability". Thus, the quantitative value of risk reflects the likelihood (magnitude of uncertainty) and the consequence (magnitude of undesirability) of an event. The undesirable consequences can appear in different dimensions such as accident or financial distress. In the present study, we are concerned with safety consequences, and therefore the focus is "safety risk".

Two well-known conceptualizations of "accident" are the following: (1) Bernner (1995) defines an accident as "not a single event, but rather a transformation process by which a homeostatic activity is interrupted with an accompanying unintentional harm". (2) Johnson (1980) viewes accidents as a conglomeration of energy and barriers rather than a process, and defines accident as an unwanted transfer of energy producing unwanted losses (e.g. injuries, damages, etc.) He believes that accidents happen because of inadequate or missing barriers. These two conceptualizations are rated best by some references (e.g. Fahlbruch et al., 2000) based on ten dimensions, such as being realistic, comprehensive, consistent and functional.

3.2.2 The Interaction of Safety & Other Organizational Performance

Safety is often not the reason for the existence of an organization, but it is one of the desirable attributes of its performances. For example, the objective of a nuclear power plant is to produce electricity, in profitable way, but it should be safe as well.

Since safety is not the sole organizational output and concern, managerial decisions and organizational practices seek to strive a balance between different organizational outcomes. Therefore, an organizational safety causal model should consider the interaction of safety performance with other organizational performances. As Rusmussen (1997) states, "when safety is controlled by stating performance objectives, as is the case with generic regulation, safety become just another criterion of a multi-criteria decision making and becomes an integrated part of normal operational decision making. In this way, the safety organization is merged with the line organization".

PRINCIPLE (B)

Safety Risk is one of the organizational outputs that influences, and also is influenced by other organizational outputs such as profit and quality.

3.2.3 Safety Performance & the Concept of Deviation

A simple conceptual model of the path of influence of organization on safety performance of a technical system (e.g. nuclear power plant, aircraft) is shown in

Figure (3.1) where the points of interface between the technical system and organization are the individuals in charge of its operation and maintenance.

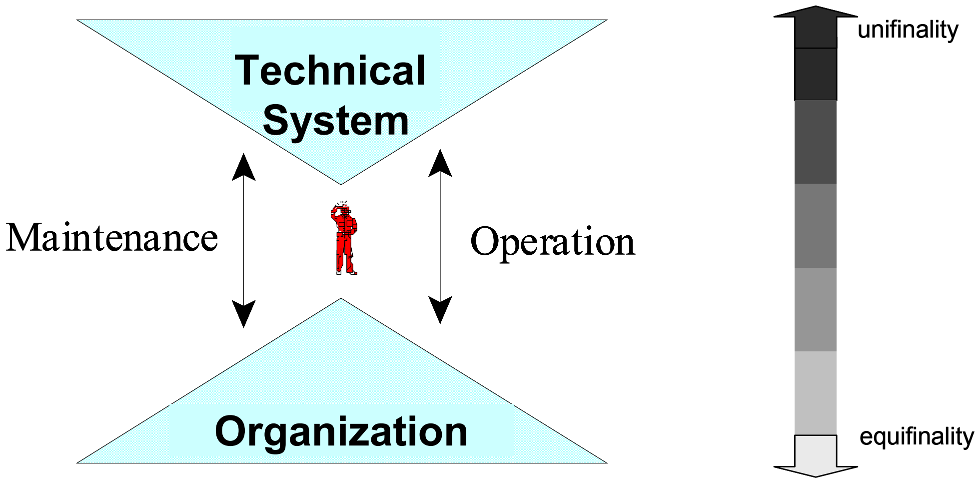

Figure 3.1 Operation and maintenance actions as links between

This simple model captures the majority, if not all, paths of organizational influence for the post design and installation phase of a system's life cycle. Arrows at interface points go in both directions, symbolizing the interactive and often dynamic nature of influence.

The organizational safety risk is a measure of deviation of organizational safety output (e.g. technical system safety performance) from a normative level of safety. Now, the question is whether or not we can extend this deviation-based concept to the lower levels in the Figure (3.1), including individuals in directly charge of the technical system and the supporting related organization. We argue that the concept of "error" and "deviation" can be clearly defined for the technical system and the individuals directly operating and/or maintaining it, but this concept should not be extended to the internal factors (e.g. emotional and cognitive ones) and external factors (e.g. team and organizational ones) affecting the performance of individuals.

In order to support this statement, we move the discussion to two conceptual terms, i. e. “equifinality” and “unifinality” (e.g. Katz and Kahn, 1978, Sharit, 2000). Unifinality refers to situation where there is only one way for the system to yield its product. In contrast, equifinality depicts the case that the product of the system can be brought forth in different ways. According to Katz and Kahn (1978, p 30) such “a system can reach the same final state from differing initial conditions and by a variety of paths”.

As shown in Figure (3.1), technical systems are mostly located at the “unifinality” side of the spectrum. In these cases there is a limited number of ways for a technical system to function “correctly”. In contrast, organizations are often located at the “equifinality” side of the spectrum. That is, there are multiple ways that an organization can reach the desirable performance. Considering that technical systems mostly lean towards “unifinality”, any deviation from the “correct” way of interacting with the system is an “error” on the part of individuals directly working with the technical system. The reference points for these individuals’ errors are the system needs. This concept was introduced in the IDAC human reliability framework (Mosleh & Chang, 2004) in order to link system and human performance failures. This deviation is similar to the concept of “Δ” in Degani and Wiener’s four “Ps’ theory (1994): Philosophy, Policy, Procedure, and Practices. They hold that it is the underlying management philosophy that leads to policies, and the policies in turn lead to procedures. Procedures are the way the activities are supposed to be done.

Practices are the way the activities are actually done by operators. The said authors define "Δ=|Practices -Procedures|" as an operator's deviation from procedures, and these deviations lead to the unsafe system outcome. Following this discussion, it is then meaningful to specify "error" for the individuals' action at the sharp end of system deviation from safe operation.

Nevertheless, these individual errors are the output of the organization, and should be only a starting point to search for the root causes. Reason (2003) refers to this as a principle of error management: "Errors are consequences rather than causes".

On the other hand, when we focus on the underlying factors (individuals' internal performance shaping factor, and organizational factors) that produce those "sharp end" actions (performances), determining "error" for a single factor is not meaningful. In other words, it is possible that different configurations of an individual's internal and organizational factors create the same individual output performance. Hence, for these factors, "error" can not be clearly defined independent of other factors. This is one of the major challenges of this line of research. As Bier (1999, pp 707-708) points out, "there is no one "correct" management style, corporate culture, or organizational structure". Several different combinations of the states of organizational factors and different structures may produce the same organizational output.

As a simple example, two organizations A and B can perform safely even though they have two different combinations of quality levels of their "training" and "selection" system. For instance, organization A may have a "medium" quality training and a "medium" quality selection system, while, organization B has a "low" quality training and a “high” quality selection system. The level of individuals’ knowledge which is the result of joint effects of training and selection can be the same for both organizations leading to the same level of safety performances. In this case, the “low” quality of training in B does not automatically translate into a failure in B’ s training.

Now, consider organization C with a “low” quality training and a “low” quality selection system that may lead to an unsafe behavior. Regardless of the fact that the interactions of training and selection systems have created some circumstances that lead to accidents, a post-accident analysis may define the failure or inadequacy of the training system as the root organizational cause of the accident, whereas the same level of training has not led to an accident in organization B. In other words, an organization can have different configurations of factors and reach a safe (or unsafe) performance. In other words, it is not necessary to find a series of failure that need to line up to lead to an organizational failure, as it is implied in Reason’s Swiss Cheese model (Figure 2.3).

The output performance is the result of combined effects of influencing factors. It may create circumstance where none of the factors individually has any problem, but their interactions may result in accidents. This concept resembles the polarization effect. It is possible to see through each of two transparent plates individually, but if we overlay the two plates at a particular angle, light will be blocked and it is not possible to see through them anymore (Figure 3.2).

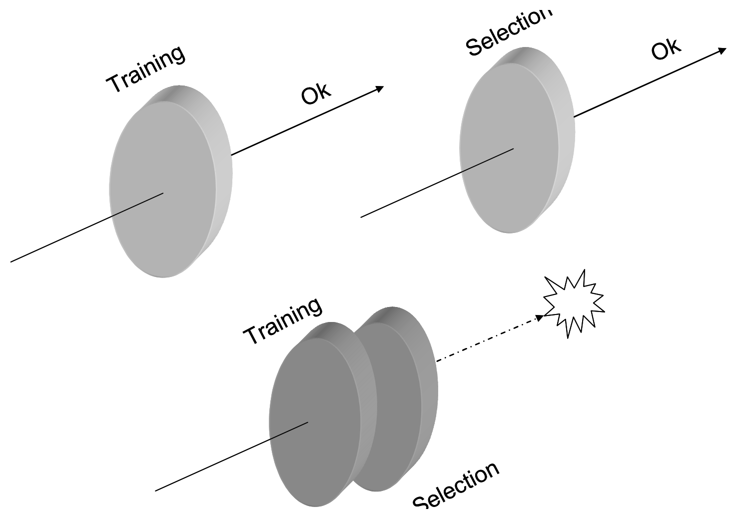

Figure 3.2 Polarized glass analogy for combinational effect of factors

This discussion is related to the concept of "fit" (Ostroff, C, Schulte,M., in press) and specifically "system fit" in organizational psychology. System fit is the degree of alignment between different elements of a system (such as the human resource system and organizational culture). Bier (1999, p.708) also refers to fit and states that "the study of management and organizational factors is difficult, in part because there is no one "correct" management style, corporate culture, or organizational structure. Rather, these various elements must be consistent both with the demands of the organization's environment (a viewpoint known as "contingency theory") and with each other (configurational theory")". For example, system fit would be the extent of consistency of the messages conveyed from different elements of the organization, regarding the extent to which safety is desired and rewarded in that organization. According to Bowen & Ostroff (2004), individuals seek consistency in their environment, and misalignments of the elements of a system will result in inconsistencies in signals and messages received from their environment.

The argument about combinational effects questions the validity (or at least the generality) of organizational accident model developed by Reason (1990). In his Swiss Cheese Model, he proposes that the top managers' error leads to the supervisors' error, which prepares the grounds for individuals' active errors, and these may lead to accidents. A German research group tried to extend the Reason model and one of their conclusions was: "the renouncement of the term "error" or "failure". …the term indicates liability or blame, an "error" can be defined only according to consequences and identified therefore only by hindsight. This leads to difficulties with regard to "failures", such as erroneous management decisions taken years ago." (Fahlbriuch et al., 2000) In other words, performance is a collective characteristic of an organization that emerges from the interaction of its elements. This concept can be compared to the macroscopic thermodynamic effects which can only be explained as the collective result of Brownian movements of the molecules rather than their individual states.

Along with this discussion, Rasmussen (1997) highlights the transition of risk analysis frameworks from models of "deviation from normative performance" to the modeling of actual behavior. He suggests moving from models such as Management Oversight and Risk Tree (MORT Johnson, 1980)), which is based on "less than adequate management decisions", and Swiss Cheese that is based on "management error", to a modeling based on "actual performance".

PRINCIPLE (C)

C_1 : The organizational safety risk can be measured as a "deviation" of organizational safety output from a normative level. The concept of "error" and "deviation" can be clearly defined for the technical system and the individuals directly operating and/or maintaining it, but this concept should not be extended to modeling the internal factors (e.g. emotional and cognitive factors) and external factors (e.g. team and organizational factors) affecting the performance of individuals.

C_2 : Analyzing the effects of organizational factors on safety calls for theoretical understanding of how the organization performs .

C_3 : The causal model and selected technical approach to implement this theoretical understanding need to be capable of capturing the "collective" nature of organizational safety performance.

3.3 Level of Analysis

The idea of perceiving an organization as a multilevel system is prevalent in most of the earliest organizational theories such as Lewin's field theory (1951), socio-technical systems theory (Emry and Trist, 1960), and Katz and Kahn's (1966) social organizational theory. Yet, this idea has not been adequately in studying of organization. Most of these studies break down systems into organization, group, and individual levels, with different related disciplines and theories. Over the last two decades, organizational science has moved toward filling the micro-macro gap in theory and research, developing well-defined multilevel frameworks. Multilevel theories integrate macro- and micro-organizational perspectives, taking into consideration the relationships between constructs on different levels of the analysis. (Kozlowski et al., 2000) Align with this evolution in organizational science, considering multilevel perspective is a principle of theory building for organizational safety risk theory.

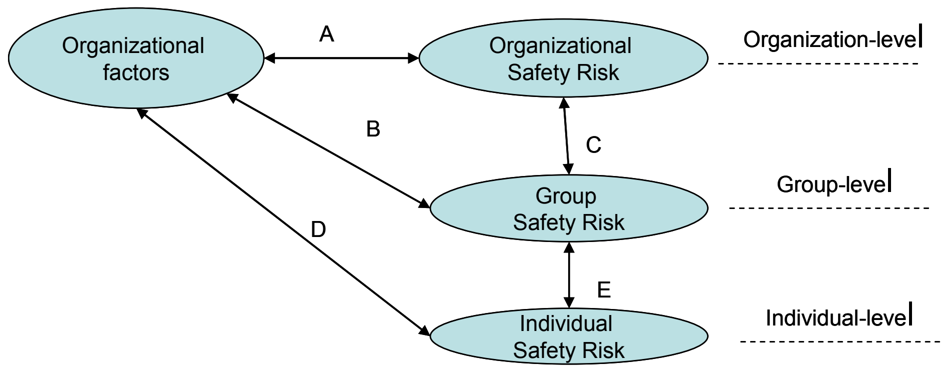

Figure 3.3 Multi-level relations between organizational factors and organizational safety performance

Since organizational safety risk is an organizational outcome, the relation between organizational factors and organizational safety risk can be studied either at the organization-level (A) or with a cross-level analysis (B-C or D-E-C). (see Figure3.3)

An organization-level accident causation theory may satisfy safety risk prediction, but it is not appropriate for risk management. Managing risks needs understanding explicit relations in order to analyze the effects of changes in the contributing factors. Since the effects of organizational factors on accidents are caused through individuals operating or maintaining the system, a causal model that analyzes the explicit relations of organizational factors on risk should be a cross-level one.

In other words, there is a need for a framework that can integrate the macro and micro perspectives. Macro analysis studies relations in the aggregate level and ignore the variations in individuals. In contrast, the micro perspectives studies how the variations among individuals influence individual performance. No single-level perspective can effectively model the organizational behavior. The macro perspective neglects the interactions among individuals as well as the process of their influence rising to higher-levels. On the other hand, the micro perspectives can not adequately consider the effects of contextual factors. (Kozlowski et al., 2000) For example, a macro research on safety can study the effects of organizational investments in training or on organizational safety performance. In contrast, a micro research can show how an increase in individual cognitive ability can increase the individual's safety performance.

The point is that safety output of an organization is a collective effect of different individuals in different units with a variety of job descriptions, for example technicians and inspectors in maintenance units and operators in an operation phase. Since the effects of training on each of these individuals can be different, and also because the interactions of their performances lead to the organizational safety performance, therefore the impacts of training on organizational safety performance has different paths of influence with different strengths. Knowing these explicit paths is necessary for decision makers that are concerned with optimizing organizational factors for a maximum performance.

Rusmussen (1970) also mentions this point in his paper explaining the modeling problem for risk management, stating that "we need more studies of the vertical interaction among the levels of socio-technical systems with reference to the nature of the technological hazard they are assumed to control". He argued that risk management needs cross-disciplinary studies that consider risks involving all levels of society.

PRINCIPLE (D)

a) A comprehensive organizational safety theory mandates a combined macro- and micro-organizational perspective. Therefore, organizational safety theory should be built in a "mulit-level" framework.

b) When "risk management" is the objective, a "cross-level" organizational causation theory is needed."

3.4 Factor

The first essential element of a theory is called *factor,* also referred to under such terms as "construct" and "variable" (e.g. Whetten, 1989, Bacharach 1989). There is some ambiguty about the difference between construct and variable in the literature. Some references (e.g. Bacharach 1989) make a distinction between construct and variable by specifying them as unobservable and observable factors respectively. Here, we use the definition given by (Kozlowski & Klein, 2000, p.27) that defines construct as "an abstraction used to explain an apparent phenomenon", and it can be either observable (e.g., unit size) or unobservable (e.g., safety climate). The *content* of a construct may include different factors, which are used to measure that construct, and those are defined as variable here. For example, climate is a construct that is measured by variables such as "employees' shared perception about the reward system" or "employees' shared perception about the reporting system".

In building a theoretical understanding of complex phenomena, the content of factors (or elements) and their links (relations, interactions), provide a powerful, almost universal language. These notations may be use in a very explicit way or only implicitly. In either way one could view "factors" and "links" as essential ingredients of models and theories and express that the smallest building block is a set of two factors and a link.

PRINCIPLE (E)

The smallest building block of a causation theory includes two factors and a link. (See Figure3-4)

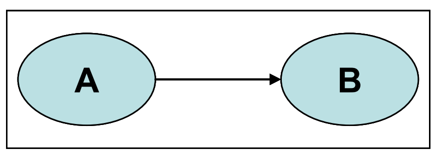

Figure 3.4 The smallest building block of a theory

The following describes three important issues related to the factors of organizational safety theories: level, measurement, and selection of the factors.

3.4.1 The Level of the Factors

Constructs can be found either on individual-levels or on unit-levels. Unit refers to any entity composed of two or more individuals such as groups, divisions, and organizations. In organizational literature, many problems emerge because of a misspecification of the level of constructs, and therefore the level identification of the factors should be accomplished in the early stages of the theory building process. Kozlowski & Klein (2000) distinguish three types of unit-level constructs: global, shared, and configural. Global unit constructs are single-level phenomena that are originated and revealed at the unit-level. "Organization size" and "organizational practices" (e.g. human resources functions) are examples of global constructs. They represent the unit as a whole, but they have an identity (or objective) separate from unit members' social and psychological characteristics. In other words, there is a reality about organization size and the quality of its practices (e.g. human resources functions) that don't originate from employees' psychological processes.

In contrast, the shared and configural constructs originate at individual-level perceptions, values, cognitions, and behavior, and emerge at the higher levels. Shared unit constructs (e.g., group climate) describe the common characteristics of the unit members, but configural constructs (e.g. diversity, pattern of individual perceptions) show the pattern or variability of unit members' characteristics. As another example, team performance can be assumed as a configural phenomenon when it emerges from the combination of team members' performance with different but interdependent tasks. (Kozlowski et al., 1999) The shared and configural constructs emerge from *composition* and *compilation* process, respectively. (These will be explained later in Section 3.5.3)

PRINCIPLE (F)

Theorists must specify whether their constructs are individual-level, global, shared, or configural. If a construct is shared or configural, the level of the construct, the level of its origin, and the nature of the corresponding emergent process should be specified.

3.4.2 Measurement & Selection of the Factors

3.4.2.1 Comprehensiveness & Parsimony

Two important and interrelated issues are "*selection*" and "*measurement*" of the factors. Different safety studies with different measurement perspectives have selected dissimilar sets of factors that influence safety. Figure (3.5) shows the conceptual relation between supporting fields and theories, measurement, and reality of a safety causal model. The layer at the bottom represents the model of reality of the safety causation mechanism in an organization. Different supporting fields and theories (the top layer) view safety causation through different measurement perspectives (the middle layer). Thus, each field looks at different parts of the organizational safety causal model (measurement "bases") and utilizing different measurement "methods". For example, the literature on safety culture (e.g. Cooper, 2000, Cox&Cox, 1991) & safety climate (e.g. Zohar & Luria, 2005, Griffin & Neal, 2000) mostly focuses on psychological causes of safety and with perception survey as the main measurement method. On the other hand, safety management literature (e.g., Kennedy & Kirwan, 1998) primarily considers organizational safety structure and practices using objective auditing measurement approaches. Yet other disciplines (e.g. *PRA*) mainly focus on direct causes of accidents.

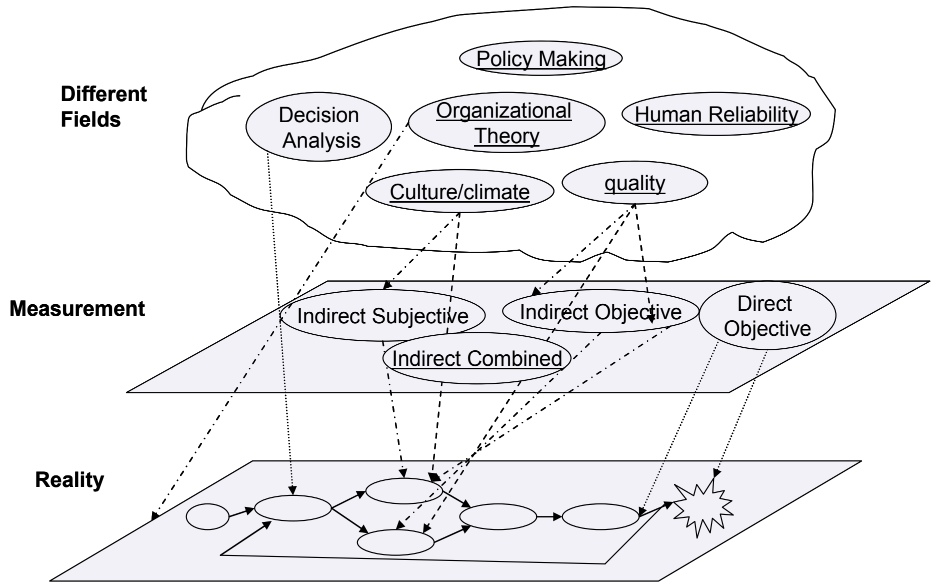

Figure 3.5 Conceptual relation between supporting Fields & Theories, Measurement, and Reality in Organizational safety causal modeling

Complex technological systems are characterized as "open" systems, as there are large numbers of dynamic interfaces with outside organizations, commercial entities, individuals, physical systems, and the environment. Figure (3.6) provides a visual account of the various dimensions of this complexity. The external environments include the physical, the regulatory, and the socio-economic environment. At the intersection of these environments, the physical system is operated and maintained by one or more organizations, through individuals interacting directly with the physical system. All interfaces are dynamic, and interactions and interdependencies are subject to changes in manners that may or may not be planned or anticipated. A comprehensive approach to analyzing and assessing the safety performance of such systems would have to clarify the roles and effects of these various elements in an integrated fashion.

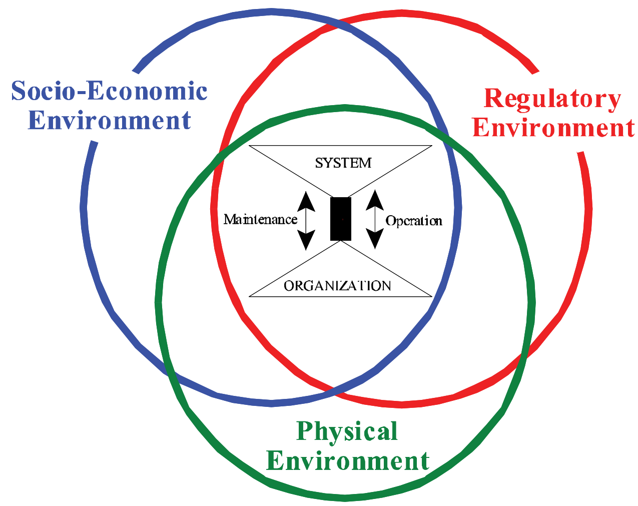

Figure 3.6 Domains of a comprehensive system approach to safety analysis

"Comprehensiveness" means the organizational safety causal model should include direct (e.g. hardware, operators) and indirect factors (organizational root causes) associated with system safety. It should cover the effects of external environments including the physical environment, the regulatory environment, and the socio-economic environment on the safety performance.

Comprehensiveness is required at both levels of model and construct. At the model level, theorists need to make sure all relevant constructs are included in the theory (Whetten, 1989). At the construct level, all relevant dimensions of constructs need to be included in a construct (this is also related to measurement issues for a construct and will be discussed in the next section.)

On the other hand, theorists should avoid unnecessary complexity by excluding factors that have little effect on the model output. This is called "parsimony". (Whetten, 1989)

PRINCIPLE (G)

a) *The organizational safety causal model should integrate the social (e.g. safety culture and climate) and structural (organizational safety structure & practices) aspects of organization that influence safety.*

b) *Inclusion of the factors in the theory should be in an optimum manner with respect to two competing concepts of "parsimony" and "comprehensiveness".*

3.4.2.2 Measurement Methods

The measurement discussion in the context of organizational safety risk modeling highlights two important questions: (1) how to measure the factors and links (link will be introduced in Section (3.4)) in the safety causal model, and (2) which aspects of the accident causation need to be measured. The first question is related to different safety measurement "methods", and the second refers to the safety measurement "basis". Answers to these questions are scattered across diverse fields such as psychology (e.g. methods of data collection in organizational psychology mentioned by Jex, 2002), quality studies (e.g. auditing approaches), and different safety studies, such as safety data collection methods (e.g. data collection in task analysis suggested by Kirwan, 1998), safety data sources (e.g. Hale & Hovden, 1998), quantification approaches of safety causal models (e.g. rating and weighting of the factors mentioned by Φien, 2001), safety auditing tool (e.g. The Management Oversight and Risk Tree (MORT; Johnson, 1980)and safety performance indicators (e.g. Kjellen, 2000).

The confusion in this subject mainly comes from mixing the two aspects of measurement, i. e. “method” and “basis”. The present discussion is an effort to clear up the confusions.

Measurement is a mean to learn the state or value of a factor (model element), perhaps in terms of the states or values of “attributes” or dimensions of that specific factor. These attributes are defined consistent with the nature of each factor. For example, the attributes of technical factors, such as equipment calibration and test practices, should be developed using the manufacturer’s standards. The attributes of some human-related factors, such as selection and reward systems, should be specified using human resource literature (e.g. Ostroff, 1995). Some of these attributes may be covered by regulatory policies and standards.

The factors of the safety causal model can be measured using subjective and objective measurement methods. *Subjective measurement* means specifying the state of a factor on the basis of the organization members’ perceptions. In other words, the source of measurement in this case is employees’ perceptions. The instrument for measurement is often in the form of a surveys or interviews. These can in turn cover the entire organization/group members, a sample, or only a small number of experts in the organization (e.g. supervisors and mangers).

Objective measurement refers to the case where the person (or group) in charge of measuring the factor objectively assesses the compliance of the factor with respect to its attributes. In this case, the source of information is assessors’ observations of the safety behaviors (using a Behavioral Checklist) and/or inspecting and auditing of the organization. Objective measurement can be either “on-site” or “record-based” (organizational records, reports, databases) or a combination. Obviously objective measurement is not limited to compliance-based assessments, and is also used for nearly all observable properties (e.g., organization size).

Subjective and objective methods can be either qualitative (e.g. high, medium, and low) or quantitative (e.g. the scale 1-10) or a combination of both. While some references (e.g. Φien, 2001) use the term *safety performance indicator* to mean mostly the quantitative objective measurement as defined here, we believe that safety performance indicators can be any factor in the safety causal model measured by its most fitted measurement approaches.

In some cases, it may be necessary or beneficial to combine different measurement methods for the same factor. Two combinations can be envisioned: “*complementary*” and “*supplementary*”. Complementary refers to the case where different attributes of the factor are measured with different methods. On the other hand, in supplementary combination, all attributes of the factor are measured with both measurement methods, providing additional information about that factor. The purpose in both complementary and supplementary approaches is to capture the highest amount of information on the *actual* state of the factor from different perspectives. The combinational approaches provide more accuracy, but they require more time and cost more. A Bayesian representation can be used in order to facilitate explaining the relation between the real state of a factor and its measurements. More detail explanation of a proposed Bayesian combinational approach is in Chapter 4.

PRINCIPLE (H)

H_1: Measurement Methods

Factors of the organizational safety theory can be measured with three different methods: objective, subjective, and combinational. The selection of the measurement method need to reflect (1) the type, the level, and the underlying theoretical model of construct, (2) the required accuracy, and (3) the availability of information.

Measurement method for individual-level constructs

Naturally, individual-level constructs should be assessed at the individual level. The individuals' psychological constructs, such as motivation and satisfaction, obviously could only be measured using subjective measure. Some observable and documented individual-level factors, such as individual age, demographic characteristics, or years of experience can be assessed with the objective method. For example, an assessor can directly observe or get this information from the organization records. (e.g. Kozlowski & Klein, 2000) The quality of individuals' physical workplace (e.g., light, climate), tools, and procedures, also can be assessed by assessors' (auditors') inspection.

On the other hand, it can be argued that relying solely on either of the measurement methods (objective or subjective) for assessing the state of physical work place conditions, procedures, and tools could be misleading. For example, the auditor might approve of a certain physical work place (e.g., lighting, air conditioning) state, but since this is only a snapshot of that work place, the real condition may be better captured by accounting for the workers' perception of their work environment. In contrast, maintenance crew may perceive that their procedures are good, but the objective auditing of the process and documents may indicate deficiencies. Thus, a better approach for these types of individual-level factors would be supplementary combination of objective and subjective measurement.

Another individual-level construct is “individual performance” that can be measured either objectively or subjectively or combined. In the objective type, the assessor can observe and fill out the behavioral checklist or record the operators’ unsafe acts in a specific period of time (e.g., Zohar & Luria, 2005). The other possibility of objective measurement of safety performance is assessor’s use of organizational reports on human failure events. In the subjective category, a supervisor may describe his or her individual subordinates’ performance (e.g. Kozlowski & Klein, 2000). Another subjective measure is a self-reporting of safety behavior, based on individuals’ own perception about their safety performance (e.g. Fogarty, 2004). The ideal method for measuring an individual’s safety performance is to have a comprehensive objective record of his/her unsafe acts. But obviously objective measurement faces difficulties such as the small number of observations, and unreliability of organizational recording and reporting. Faced with limitation of information, it is prudent to use all possible sources of information and combine (i.e. use a supplementary approach to) the objective and subjective measures of individual safety performance.

PRINCIPLE (H)

H_2 : Measurement methods for Individual-level constructs

a) *The individuals' psychological constructs (e.g. psychological climate) should be measured using subjective method.*
b) *The observable and documented individual-level factors (e.g., individual age, demographic characteristics) should be assessed using objective method.*
c) *The quality of individuals' physical workplace (e.g., light, air-condition), tools and procedures, can be assessed by assessors' (auditors') objective inspection. But for more accurate assessment, a combination of objective and subjective measurement should be considered.*
d) *The ideal method for measuring an individual's safety performance is to have the objective record of his/her unsafe acts. When faced with practical deficiencies for objective measurement of individual safety performance, supplementary combination of the objective and subjective measures should be considered.*

Measurement methods for global constructs

Some *Global constructs* which are observable characteristics of organization (such as its size, or the number of accidents) are measured naturally by objective measurement methods. Some other global constructs, such as the quality of organizational practices (e.g., human resource functions), can be measured either objectively or subjectively or combined. The assessor can directly audit the functions and the organization's record. The assessor can also obtain information subjectively through interviews or surveys of managers. (Kozlowski & Klein, 2000) Kozlowski & Klein (2000) indicate that for unit's functions, there is no need to ask all individuals within a unit, and a single expert (e.g., manager) can be a reliable informant. But the reality of some attributes of functions can be better measured by employees' perceptions. For example, two of the attributes of training, a human resource practice, mentioned by Ostroff (1995, p.6), are: (1) to "have formal orientation programs that provide new employees with information about the company and the job", and (2) to “develop mechanisms so that employees are supported or rewarded for using their newly learned skills on the job”. One can argue that the first of these two attributes can be more easily measured objectively, while the second one is more subjective. Employees who receive this reward system can better judge to what extent those mechanisms are supportive and rewarding. Therefore, the assessment of the real state of the training can be captured by a complementary combination of subjective and objective measurements.

Now consider the case of selection, a human resource function, and one of its specific attributes, namely to “provide information to job applicants that realistically describes the job and company”. (Ostroff, 1995, p.6) In this case, the assessor can measure the state of the attribute by objective auditing of the information provided to the applicants. This attribute can also be measured by asking employees’ perceptions about the information provided to them through the employment process. Supplementary combination of these two pieces of information can provide a more accurate assessment of the state of selection.

One argument in support of using the supplementary measurement method is the practical limitation of some objective methods. For example, auditors only get a snap shot of the organization and often a very small sample of the character. In contrast, perception surveys (subjective measurements) can capture some parts of reality that are missed by objective auditing. As Pidgeon (1991) states, the term “perception” implies a potential for bias away from some presumed objective standard or stimulus. Besides, Ostorm et al. (1993) named some advantages of perception surveys for measurement including “ (1) the effectiveness of safety efforts cannot be measured by traditional procedural-engineered criteria like safety reviews, audits, and inspectors; (2) the effectiveness of safety efforts can be measured with surveys of employee perceptions; (3) a perception survey can effectively identify the strengths and weakness of elements of a safety system; (4) a perception survey can effectively identify major discrepancies in the perception of program elements(between hourly rated employees and the level of management); and (5) a perception survey can effectively identify improvements in and deterioration of safety systems if administrated periodically".

Obviously subjective measures also have their own limitation. For example, employees' perception about organizational safety practices (e.g., training) can be inadequate, since supervisors often function as interpretive filters for the employees, thus masking the reality of the state of the factor as viewed through individuals' perceptions. For this reason, relying solely on objective or subjective measurement for a given attribute could be misleading.

PRINCIPLE (H)

H_3: Measurement methods for Global Constructs

- *a) Global constructs should be assessed at the unit level.*
- *b) The observable global constructs (e.g., organization size or the organization's number of accidents) should be measured by objective measurement.*
- *c) The best measurement approach for other global constructs, such as the quality of "organizational safety practices" (e.g., human resource functions) is the combinational approach. Subjective opinion of a single expert (e.g., manager) is a possible, but less desirable measure.*
- *d) In the case of combinational measurement of "organizational safety practices" (e.g., reward system), better estimate of reality can be obtained by separating the attributes of the function into observables (e.g., frequency of training) and unobservables and by using the most appropriate measurement method for each set of attributes.*

Measurement methods for shared constructs

Shared constructs (e.g., safety climate) originate from the individual psychological level, and thus there is no doubt that they should be measured subjectively through the unit members' perception survey. One important issue in the measurement of shared constructs is construct validity, evaluated through within-group variance. The aggregate (mean) value of the measure should be assigned to the unit if the within-unit variance is in the limited range. (e.g., Hafmann & Stetzer, 1996, Kozlowski & Klein, 2000) There are two approaches for the measurement of within-group variance, including consensus or agreement based approach and consistency or reliability-based approach. The detail explanations about the aggregation issues are not the concern of this discussion and can be seen in the related references. (e.g., Bliese, 2000)

The other challenge about shared constructs is item construction for survey instruments. Some have suggested guidelines for item construction, such as focusing the respondents on the description rather than the evaluation of their feelings (James & Jones, 1974) and referencing a higher level, instead of the level of measurement (e.g. Klein et al. 1994).

PRINCIPLE (H)

H_4: Measurement methods for shared constructs

- *a) Shared constructs originate from the individual psychological level, and thus should be measured subjectively as an aggregate of unit members' perceptions.*
- *b) Construct validity of the aggregated measure needs to be established by examining patterns of within-group variance.*

A measurement method for configural constructs

Kozlowski & Klein (2000) have defined two different types of c*onfigural* constructs: *descriptive* and *latent*. The former refers to observable features of units, such as the pattern of age in unit members, and thus are cases of objective measurement. In contrast, latent constructs refer to unobserved properties, such as the pattern of individual perceptions, and these should be measured subjectively. There are different techniques that can combine the individual-level measures and create the configural constructs. Depending on the theoretical definition of the constructs, these techniques can vary, for instance "minimum and maximum", "indices of variation", “profile similarity”, “multidimensional scaling”, and some modeling techniques such as “neural nets”, “net-work analyses”, “system dynamics” and other nonlinear models. (Kozlowski & Klein, 2000, p.34) For example, the pattern of age in the unit can be shown by indices of variation in age, but the team performance can be estimated from a non-linear combination of individuals’ performances. Some further discussions on modeling techniques will follow in Chapter 4.

PRINCIPLE (H)

H_5: measurement method for configural constructs

a) *Descriptive configural constructs should be measured objectively. Latent configural constructs should be measured subjectively.*
b) *Configural constructs originate at the level of the individual, and depending on the theoretical emergence reflected in the configural properties, the individual-level data should be combined with variety of techniques from simple (e.g., indices of variation) to complex (e.g., non-linear models).*

The role of perception as a measurement method and Internal PSF

PRINCIPLE (I)

Perception plays two different roles in safety modeling: (1) as a measurement method, and (2) an internal Performance Shaping Factors (PSFs) for human behavior.

If the nature of a construct is perceptional, then subjective measurement can capture the actual state of that factor. If the nature of the factor is not perceptional, then subjective measurement only presents part of the reality and the actual state of the factor should be assessed by a combination of objective and subjective measurements. For example, for global constructs, when we use subjective measurement to assess organizational functions (e.g. human resource), perception plays its first role, i.e. as measurement. Experts' or employees' perceptions are the sources of information and only reflect part of the real state of the factor. In contrast, for the shared constructs, perception becomes important in its second role, namely individuals' performance shaping factor. For example, the concept of psychological climate, an individual performance shaping factor, is the individual's perception of organizational practices. Therefore, perception measurement gives us information about the actual state of the psychological climate, because the nature of that construct is perception.

The perceived state of a specific factor can be substituted with different paths of influence in the safety causal model. Theorists need to consider these overlaps in order to avoid misspecifications of causalities in the model. In view of these two roles of perception, one can say that individuals' perception about a factor can have different paths of influence in the safety causal model. For example, an individual's perception about training is an element of the psychological safety climate (described in Chapter 4), which is an internal PSF with impact on human behavior through his/her motivation. On the other hand, this perception is a subjective measure of training and reflects part of the real state of training in the organization. The path of influence of the reality of training in the safety causal model is essentially through its relation to the individual's level of knowledge.

<u>The effects of measurement on dependencies of the factors</u>

The interdependencies of factors are also strongly related to their measurement approaches. For example, training and reward system measured based on perception survey can be highly interdependent because of the common influence of supervisors. In contrast, objective measurements of these two factors are far less interdependent.

PRINCIPLE (J)
The interdependencies of factors are strongly related to their measurement approaches.

3.4.2.3 Multi-dimensional Measurement Perspectives

Different measurement perspectives for organizational safety can be identified through combinations of measurement "methods" and different measurement "bases". There are two kinds of measurement bases: *direct* and *indirect*. Direct measurement captures organizational safety output (e.g., frequency of accident). Indirect measurement accounts for safety enablers or the safety causal factors (e.g., safety climate, safety practices).

Direct measurement can be subjective, objective, or a combination of both. The direct subjective measurement can be achieved through questionnaires and surveys of the organization's members about their perception of the safety of the organization. This is a subject of study in the *risk perception* field. The value that is measured in this approach, sometimes, is not a proper measure of the organizational safety state, since forming an opinion about the overall organizational safety output is often difficult for organizational members, especially in High Reliability Organizations (HRO) (e.g., airlines and nuclear power plants). Since employees' risk perception has an impact on their performance (e.g., turnover) this measurement has some applications for managerial decision making as well.

Direct objective measurement can be either based on safety outputs (accident/incident data), or model-based, or combination of both. Measurement based on safety outputs means objectively measuring (either on-site or record-based) the number of accidents/incidents, which are sometimes very rare for HROs. Model-based measurement refers to the use of risk or safety assessment models (e.g., PRA) to estimate level of risk or safety, based on more frequent, but less catastrophic occurrences. For example, using historical data, the frequency of hardware and operator failures are estimated and used in technical system risk scenarios in order to calculate the total risk of the system. The other approach is a supplementary combination of model-based and safety output-based measurements that integrates two different kinds of information and reduces the uncertainty. This combination can also be employed using Bayesian approaches. One consideration about using Bayesian methods for this case is to avoid the overlaps of the two sets of information.

Another possibility is supplementary combination of direct objective and direct subjective measurements. This means that employees' belief about total safety/risk of organizations is combined with a model-based assessment of total risk, as another piece of information (using the Bayesian method described before).

For three key reasons, indirect measurements may be preferred over direct measurements. First, since direct measurements assess the organizational safety outputs, by definition they cover the past or partly the current state of organizational safety. Indirect measures, on the other hand, evaluate the state of organizational safety enablers whose impact will be revealed in the future (and partly current) organizational safety state. The second reason is the lack of accident or even incident data for a specific organization. Thirdly, for the purpose of risk management and risk prevention, the root causes and indirect factors need to be measured and analyzed.

Indirect measures can be restrictive or non-restrictive. Restrictive refers to the case where indirect factors are assessed either subjectively or objectively. Restrictive-objective measures are mostly related to the *safety management* field, where organizational practices and structure are measured objectively. Restrictive-subjective measures, on the other hand, are mainly used in the *safety culture/ climate* field, where the focus is on psychological constructs (e.g., culture, climate). Indirect non-restrictive stands for the case where the measurement approaches vary for different factors of the model, covering objective, subjective and combined (supplementary and complementary) measures. For example, culture and climate are assessed with subjective methods, safety behaviors (e.g., maintenance technician actions) with objective measurements, and organizational safety practices (e.g., human resources systems) with the combination of objective and subjective methods.

A more realistic state of "organizational safety performance" can be measured by utilizing a combination of direct and indirect approaches. The purpose of this combination is also the integration of two pieces of information in order to reduce uncertainty. However, since direct measurements cover mostly the past state of organizational safety, and indirect measures evaluate the state of organizational safety enablers whose impact will be revealed in the future, combinations should be carried out with carefully considering the time confirmation of the two pieces of information. For example, based on direct measurement, the trend of the organizational safety state in a period of time can be estimated and then extrapolated to predict the future organizational safety state. The future organizational safety state can also be estimated using indirect measurements (current measures of organizational factors predict the future safety state of organizations). These two pieces of information could be combined using Bayesian approaches. One challenge for this combinational perspective is the determination of time lags. (see Figure3.7)

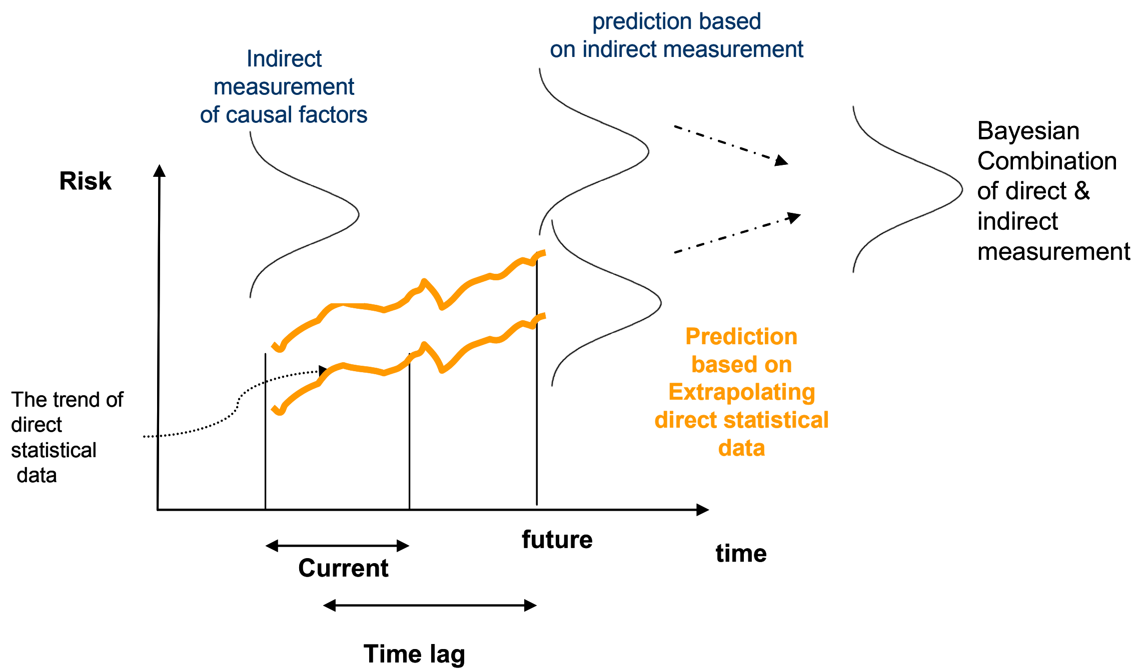

Figure 3.7 Combination of direct and indirect measurement approaches

PRINCIPLE (K)

Realistic assessment of organizational safety risk requires a multi-dimensional coverage of measurement methods (how to measure) and measurement bases (what to measure). (see Figure 3.8)

Measurement Methods

Measurement Bases

<table>
<tr><th colspan="2"></th><th colspan="3">Objective</th><th>Subjective</th><th>Combined</th></tr>
<tr><td colspan="2">Direct</td><td>2a</td><td>2b</td><td>2c</td><td>1</td><td>3</td></tr>
<tr><td rowspan="2">Indirect</td><td>restrictive</td><td colspan="3">4</td><td>5</td><td></td></tr>
<tr><td>Non-restrictive</td><td colspan="5">6</td></tr>
<tr><td colspan="2">Combination of Direct & Indirect</td><td colspan="5">7</td></tr>
</table>

Figure 3.8 Multidimensional measurement Perspectives

In summary :

- (1) The direct subjective measurement can be achieved through questionnaires and surveys of the members of the organization about their perception of the safety of the organization. This is a subject in the risk perception field.
- (2a) Measurement based on safety outputs means objectively measuring (either on-site or record-based) the number of accidents/incidents.
- (2b) Model-based refers to use of risk or safety assessment models (e.g., PRA) to estimate level of risk or safety, based on more frequent, but less catastrophic occurrences. For example, using historical data, the frequency of hardware and operator failures are estimated and substituted into risk scenario in order to calculate the total risk of the system.
- (2c) this approach is a supplementary combination of model-based and safety output-based measurement.

- (3)Supplementary combination of direct objective, and direct subjective measurement. This means that employees' belief about total safety/risk of organization is combined with model-based assessment of total risk, as another piece of information (using Bayesian method described before).
- (4) Restrictive-objective is mostly related to safety management field, where organizational practices and structure are measured objectively.
- (5) Restrictive-subjective measures, on the other hand, are mainly used in safety culture/ climate field where psychological constructs (e.g., culture, climate) are the focus.
- (6) Indirect non-restrictive stands for the case where the measurement approaches are different for different factors of the model, covering objective, subjective and combined (supplementary and complementary) measures. For example, culture and climate are assessed with subjective methods, safety behaviors (e.g., maintenance technician actions) with objective measurements, and organizational safety practices (e.g., human resources system) with the combination of objective and subjective methods.
- (7) The last possibility is the combination of direct and indirect approaches. For example, based on direct measurement, the trend of organizational safety state in a period of time can be estimated and then extrapolated to predict the future organizational safety state. The latter can also be estimated using indirect measure. These two pieces of information could be combined using methods such as Bayesian approaches.

3.5 Link

PRINCIPLE (L)
Links should be specified according to all of the following dimensions: level (single level and cross-level), nature (antecedent, measurement, and correlation), and structure (facto- to-factor and factor-to-link)

3.5.1 The Nature of the Links

Links (shown by arrows) represent relations (e.g., causality) between the factors. As Wheeten (1989) has stated, theory-oriented studies do not need to have all the relationships tested empirically, but the relationships need to be justified either by existing literature (theories) or logical propositions.

The detected relations that are only based on data and without understanding the "Whys" underlying the model, could be misleading. In general, empirical correlations are not a sign of causality. As a simple example, the sales of ice-cream and sunscreens rise when the summer temperature goes up. Statistical techniques can observe a strong relation between sunscreen sale and ice-cream sale, but neither are causes of the other one. (see Figure 3.9) These data-driven models might provide a good assessment of overall safety behaviors, but risk management needs an understanding of causal mechanisms.

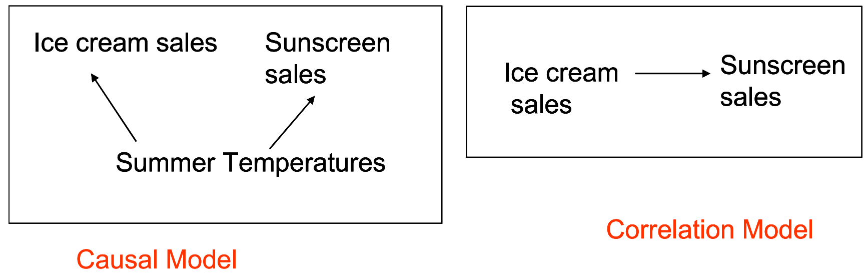

Figure 3.9 Correlation Vs. Causality

Another type of link (arrow) is the measurement "link" that relates construct to its measurement contents. For example, in Figure (3.10), the relation between the measurement contents of B (i.e., B1, B2, and B3) and factor B is of "measurement" type. The link between A and B , on the other hand indicates a causal relation between A and B ("antecedent" link).

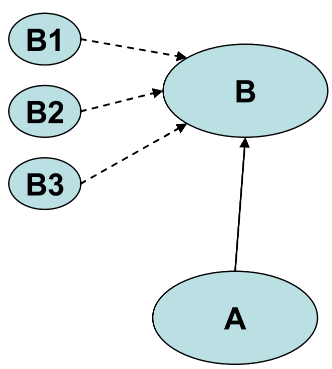

Figure 3.10 "Measurement" link vs. "Antecedent" link

PRINCIPLE (L)

L_1: The nature of the link

a) *Any link can be characterized as "antecedent", "measurement", or "correlation".*

b) *Links built based on empirical correlations are not necessarily indicative of causal relations. Antecedent links require supporting theory or logical propositions.*

3.5.2 The Structure of the Links

PRINCIPLE (L)

L_2: The structure of the link

Links are either "factor-to-factor" or "factor to link" relations. (see Figure 3.11)

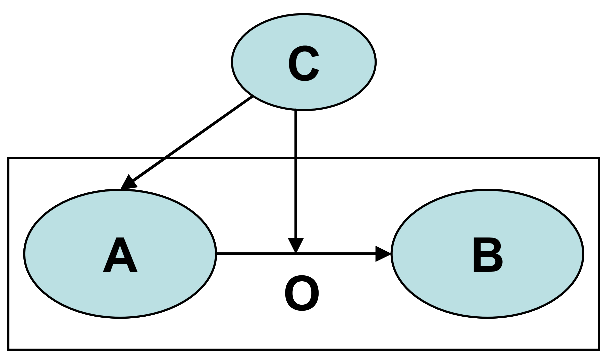

Figure 3.11 Structure of the links

An example of "factor-to-factor" links is the link between "selection" (as a human resource function) and "group safety climate" (the shared perceptions of a group about organizational safety). A "factor to link" effect is the case when a factor influences the relation (link) between two other factors. As an example, the organizational context can moderate the strength of the relationship between morale and individual safety performance. In a rather authorization organization, there are more constraints on employees' performance and the relationship between morale and individual safety performance will be weak.

3.5.3 The Level of the Links

> *PRINCIPLE (L)*
>
> *L_3: The level of the link*
>
> a) *Links can be characterized as "cross-level" or "single level". The cross-level influences can also be either "bottom-up" or "top-down".*
>
> b) *Depending on the conceptualization of higher-level phenomena, the bottom-up process can be in two forms of "composition" and "compilation". In case of a composition process, theorist must explain in detail how within-unit agreement and consensus emerges from the individual-level characteristics. In the case of a compilation, the theorists must explain in detail the theoretical process (nonlinear complex function) by which different individual contribution combine to produce the emergent phenomenon.*

An example of single-level relation is one between organizational structure and organizational outcome (a relation at organization-level). Each level of organization is embedded in a higher-level context. Individuals are placed in groups, groups in organizations, and organizations in industries. Often there are some influences (either direct or moderating) from higher-level phenomena on lower-level constituent elements. These effects are called top-down influences in the model. For example, organizational safety practices (e.g., training, reporting system, and etc.) are antecedents of individual-level psychological safety climate (the perception of individuals about safety practices). This is the direct effect of organizational safety practices on the individual psychological safety climate. In contrast, the top-down moderating effects are those where a higher level factor moderates the relationships in the lower-level unit. (Kozlowski et al., 2000) as mentioned before, for example, the effects of morale on individual safety performance would be different in different organizational structure.

The bottom-up process describes the emergence of a phenomenon from lower-level to higher-level contexts; this is a central concept in General System Theory (GST, Boulding, 1956 & Miller, 1978). One perspective of GST focuses on the collective structure at higher levels resulting from the dynamic interactions among lower level elements. For example, the interactions among atoms make the molecular structure. Another perspective looks at emergence of an element to a higher level as both a process and a structure. This perspective built on theories of chaos, self organization, and complexity, analyzes how the interactions among lower-level elements gradually and over the time create higher-level structures or phenomena. (Kozlowski et al., 2000) In multilevel organizational safety modeling, the second perspective is selected, and thus both process and structure are covered in the emergent phenomena.

There are two types of emergent processes: “composition” and “compilation”. Composition “describes phenomena that are essentially the same as they emerge upward across levels”. (Kozlowski et al., p.16, 2000) For example, the group safety climate emerges from the shared perceptions of group members about organizational safety practices (e.g., training, report system, etc.). Thus, the group and individual safety climate are the same constructs, although they are at different levels. In contrast, Compilation "describes phenomena that comprise a common domain but are distinctively different as they emerge across levels". (Kozlowski et al., p.16, 2000) For example, team performance can be the result of pattern of individual team members' performance. In other words, team performance is a complex function of individuals' performance and their interaction with each other. (Kozlowski et al., 1999) Thus, based on compilation models, a complex combination of diverse lower-level contributions forms the higher level phenomena. (Kozlowski et al., 2000)

For example, a safety causal model can be a relation between group safety climate (A_g) and group safety performance (B_g). (Figure3.12) The link A_gB_g is of an antecedent nature, it is a single-level link, and a direct relation. A_g is a shared construct and emerges from A_i, the individual safety climate. The link A_iA_g is a cross-level, bottom-up process. Structurally, it is also a direct link. Group safety performance (B_g) is a configural construct and emerges from individual factors (B_{i1} , B_{i2} , B_{i3}). The links B_{i1} B_g, B_{i2} B_g, B_{i3} B_g are all cross-level bottom-up links.

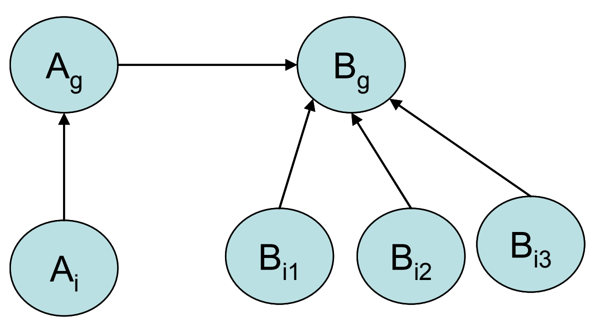

Figure 3.12 An example of different link with different nature, structure, and level

3.6 Time Dependence and Dynamics

Dynamic aspects refer to how an organization behaves in time and in the transition from one state to another. The following provides a conceptual discussion of the key dynamic issues that need to be analyzed in organizational safety frameworks. The topic covers the "time delay" between causes and effects, some composite effects such as "feedback loops" and "time scale variations", and "temporal changes" in organizations.

The first dynamic issue is the phenomenon of *delay* .For instance, in Figure (3.13), the effect of A or B on C may take place over time and with delay. Delay can lead to a composite dynamic effect, named by some authors "*time scale variation*". For example, assume A affects C in t_1 units of time while, B affects C in t_2, with $t_1 < t_2$

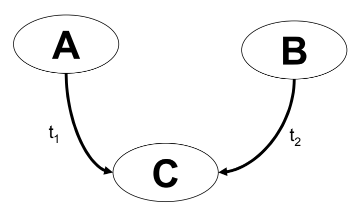

Figure 3.13 Factors A and B affecting C with two different time effects

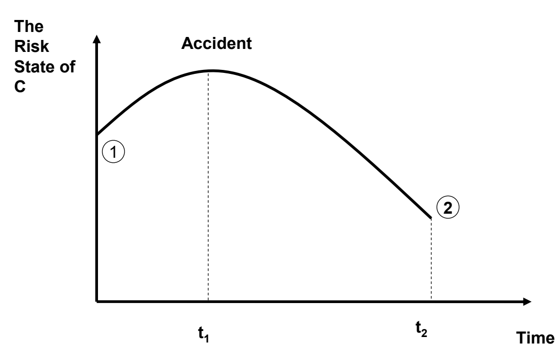

Figure 3.14 The Delay problem in the static causal model

Now consider Figure (3.14) when factors A and B change from (1) to (2), the state of C evolves from (1) to (2). At state (2), both factors A and B have affected C and resulted in a less risky state of C. But, at point t_1 , B has not yet affected C. A static causal model does not see the state of C at that point. This blind spot could be a state causing of accident. (see Figure 3.14) Some references (e.g., Sterman, 2000) have discussed this issue under the term delay, and some others (e.g., Kozlowski & Klein, 2000) utilized time-scale variations for this concept.

Time-scale variations can occur at a single-level and/or across levels. For example, at the organization-level, the effects of safety performance of organization on its financial performance through direct cost of accidents are quicker than the effects of financial performance on its safety culture. Lower-level effects are more rapid than higher-level and emergent phenomena. (Kozlowski & Klein, 2000) For example, the effects of individual-level training on individual performance occur faster than the effects of training at the organization-level on organizational performance. Individuals' performances combine through social and work interactions, and compose or compile higher-levels performances; process that take a longer period of time. (Kozlowski & Salas, 1997)

The time-scale difference between higher-level and lower-level phenomena is conceptually related to two well-known terms in human reliability, *latent condition* and *active failure,* coined by Reason (1990), in organizational accident frameworks. Reason (1990) expresses the weaknesses in organizational processes, such as decisions concerned with planning, designing, and budgeting that are transmitted along organizational pathways to the various work conditions as latent conditions. He holds that the transfer of latent conditions to the workplaces takes much longer than effects of local factors in the workplaces (e.g. inadequate tools, lack of knowledge) on an individual unsafe act (active failure).

Another composite dynamic phenomenon in organizational safety modeling is *feedback loops*. Feedback refers to the case where factor A affects factor B, and B affects A possibly through a different path of influence. Feedbacks can be either at a single level or across levels. For example, at the organization-level, organizational safety practices affect safety, and safety affects the financial outcome of the organization. Financial outcomes have some impacts on organizational safety practices through managerial decisions. There are also many feedbacks in multilevel frameworks that originate from the combination of top-down and bottom-up processes.

Normally all "feedback loops" can be unfolded over the time in which they take place. In other words, the path from A to B and the path from B to A have two different time phases, and these two cannot occur at the same time. First A must necessarily affects B, and then B will affect A in the next "time step". Since these can have different influences (f& g), we can express $B(t) = f(A(t))$ & $A(t+ \Delta t) = g(B(t))$. (see Figure(3.15))

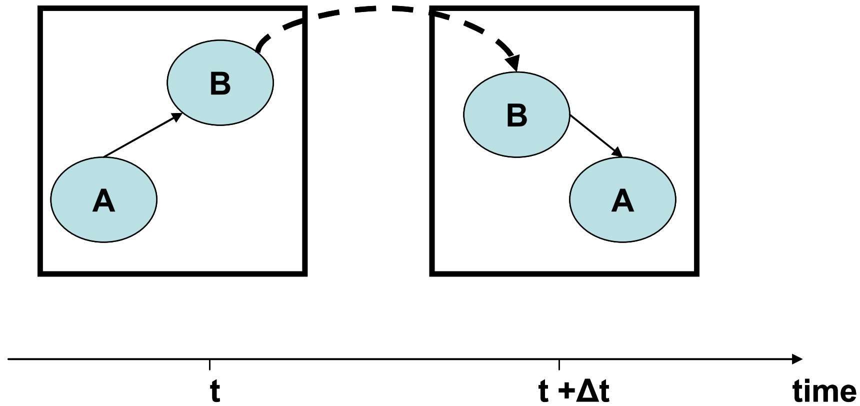

Figure 3.15 Feedbacks through the time

In a multilevel framework, a feedback loop could be the path from A to B in a bottom-up process and, while the path from B to A can describe the top-down process. For example, when the organization is at an early development stage or under extraordinary changes, the organizational culture is emerging from individual sense making and social interactions through a bottom-up process. After a period of time, the organization culture becomes mature and stable. At this stage, organizational culture has a more top-down effects on new members joining the organization. Thus time stands as a boundary condition for the model. Theorist should specify whether the model represents the mature organizations or the new ones. Time also can be considered as moderator in the sense that the direction and the strength of the links act as a function of organization maturity. (Kozlowski & Klein, 2000)

The last dynamic concern is the *temporal* changes in the organization and its elements. Temporal changes refer to any changes over time in factors or links of the organizational frameworks. For example, *temporal cycles* refer to the periods of change in organizational circumstances (internal and/or external) that affect the existence and strength of some linkages in organizations. Some references (e.g., Ancona & Chong, 1997, Kozlowski & Klein, 2000, p.24) have used the term *entertainment* refering to "the rhythm, pacing, and synchronicity of processes that link different levels". Task cycles and work flows, budget cycles, and other temporal events are examples. For example, the work flow dependency is not considered uniform over time in the group and team literature. (e.g., Fleishman & Zaccaro, 1992) At some periods of time, some synchronized acts and responses are required, and thus dependencies and couplings will be at maximum.

The levels of uncertainties about these temporal cycles differ considerably. Some of these temporal events, such as task cycles are more predictable and some of them are quite hard to model. The complexity arises not only from the difficulties in identifying those specific time cycles, but also from the impacts of those cycles on the organizational safety framework. In safety frameworks, some of these temporally cycles are due to new regulatory concerns, new participants (e.g., new CEO of the company), and new safety concerns after occurrences of major accidents. For example, Kunreuther & Bowman (1997) studied the dynamic model of organizational decision making after the Bhopal accident and showed that how constraints changed after the occurrence of the disaster.

PRINCIPLE (M)

Static organizational safety frameworks can not capture the risk originating from: (1) delay in influences, (2) temporal changes in factors and links (e.g., temporal cycles), (3) composite time effects (e.g., time scale variation and feedback loops). The direction and the strength of the links in the organizational safety model is usually a function of time. The time boundary and reference points of the theory must be explicitly specified.

3.7 Boundaries & Assumptions

Organizational accident causation theory is a statement of cause-effect relations between the elements of an organization and various types of accidents and incidents within a set of boundary assumptions and constraints.

3.7.1 The Depth of Causality & Level of Detail

One concern in specifying boundaries of an organizational safety theory is the "level of causality". The question is where one should stop the causal chain. Do we need to assume the operational managerial decisions (hiring, training, etc.) as "bottom layer" factors or it is better to move further in the chain of causality? Do we need to stop at the top managers' strategic decisions or do we need to include the regulators' impacts on them?

For example, if an organization is interested in analyzing the effects of its internal factors on safety performance, the regulatory factor is out of the boundaries of the model. Also, the manufacturers' deficiencies in the design of some parts are – despite their high impacts on safety performance of organizations- assumed out of the model boundaries as long as the organization doesn't have control on them.

As we mentioned in the Section (3.5.1), a possible type of link (arrow) is the measurement link connecting a construct to its measurement contents. A modeling choice is whether to consider a factor as "global" or "multidimensional". This is one aspects of "level of details" for the construct. For example, in Figure (3.16), it is possible to have a causal relation between A and B directly, and in this case factor B appears in the model globally. It is also possible to make different paths of influence form factor A to measurement contents of B (i.e. B1, B2, and B3), and in this case factor B appears with a higher level of details in the model.

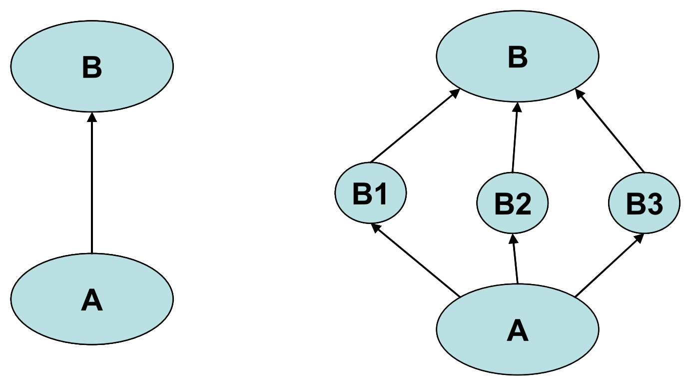

Figure 3.16 Level of detail

For example, think of factor A as “human resource system” and factor B as “safety climate”. (see Figure 3.16) The modeler can establish a direct link between these two, or he/she can observe a relation between human resource and the measurement content of the safety climate (e.g. “perception about reporting system” , “perception about training”, etc.) . The latter is modeling with a higher level of details. The decision about the level of detail depends on the importance of different dimensions of the constructs in relation to the model output. For example, if the objective is to analyze the effects of B1-B3 on safety performance, and the safety is sensitive to these factors, then it is better to consider factor B in a multidimensional way.

PRINCIPLE (N)

a) *In determining the depth of causality in the model, one needs to consider: (1) the objectives of the model (e.g. the level of the decision variables), (2) the availability of data, and (3) the level of control (which factors can be changed or controlled?)*

b) *The decision about the level of details in specifying the characteristics of a factor should reflect concerns regarding the impacts of different dimensions of that factor, and the sensitivity of the model output to those dimensions*

3.7.2 Generality of the Model

Theory building needs specifying the boundaries and assumptions in order to show how general the model is.(Wheeten, 1989) In the case of a safety causation theory, we need to specify, for instance, which aspect of the theory is general for all industries and organizations, and which ones are restricted to a specific industry. As Rasmussen (1997) states, safety studies can be divided into three categories depending on the frequencies and consequences of the potential accident: (1) Occupational safety that focus on small-scale and frequent accidents. (Fahlbruch et al. (2000) argue that occupational safety deals with intra-organizational incidents and accidents, while system safety considers the interrelationships between an organization and some extra-organizational factors), (2) Medium size and infrequent accidents (e.g., aircraft accidents), (3) very rare and unaccepted accidents (e.g. in nuclear power plants accidents).

PRINCIPLE (O)

Theorists need to specify the level of generality (all organizations, specific industry, etc.) and the scale and scope of safety concerns: occupational safety, medium size & infrequent, very rare & unaccepted accidents.

3.8 Character of Modeling Techniques

Principle (P)

Because of multidisciplinary nature of the organizational safety framework, a comprehensive technique for organizational safety framework is a "hybrid" technique. Candidate ingredients are techniques from Risk Assessment, Human Reliability, Social and Behavioral Science, Business Process Modeling, and Dynamic Modeling.

1. Risk assessment techniques such as FT, ESD, BBN in order to assess the deviation of technical system from normative level of safety (referring to principle C_1)
2. Human Reliability Technique in order to assess the possibility of errors of individuals directly operating and/or maintaining the technical system.(referring to principle C_1)
3. Social and Behavioral Science that includes Regression-based techniques such as "path analysis" and "Structural Equation Modeling" in order to "quantify" or "test" the causal relations
4. Business process modeling to represent the process of organizational practices

5. Dynamic modeling techniques to depict the dynamic aspects of framework (referring to principle M)
6. Configurational approach in order to capture the collective and combinational effects of factors (referring to principle C_3), without applying a deterministic modeling technique.

More details about the adopted techniques are illustrated in Chapter 4.

4. ORGANIZATIONAL SAFETY RISK ANALYSIS: ADAPTING HYBRID TECHNIQUE

4.1 Introduction

The focus of this chapter is on model representational schemes and quantification. There have been significant improvements over the past two decades in the sophistication of quantitative methods of safety and risk assessment, but there have not been adequate discussions on adapting the best techniques suitable for modeling objectives and boundaries. There is some debate about which "techniques" are more or less appropriate for organizational safety risk analysis. Candidate techniques for organizational accident causation theory are selected from risk assessment, social and behavioral sciences, business process modeling, and dynamic modeling techniques. In what follows, most common techniques from these disciplines are briefly compared and discussed in order to provide a guide for informed choices. This chapter provides a methodology of step by step adapting the appropriate techniques, converting them to the common technique, and creating a "hybrid" approach consistent with the principles outlined in Chapter 3. The described methodology is the second contribution of this thesis.

In each step, a number of related techniques are explained to facilitate the discussion on adaptation. *Technical system risk modeling techniques*, *regression-based techniques*, and *process modeling techniques* are explained in Section (4.2), (4.3), and (4.4) respectively. Section (4.5) explains how to adapt a common technique, Bayesian Belief Network (BBN), and convert process modeling technique and regression-based methods to BBN. Section (4.6) is a discussion on integrating *configuartional approach*, and Section (4.7) argues how we could technically involve the qualitative data in a quantitative framework. Adaptation of *deterministic* and *dynamic techniques* is described in Section (4.8). Section (4.9) is a brief discussion of adapting *human reliability techniques*, and Section (4.10) proposes a *hybrid technique* environment for realization of organizational safety analysis. Sections (4.11) and (4.12) offer complementary materials on measurement techniques and model evaluation techniques.

4.2 The Modeling Techniques for Technical System Risk & Safety Assessment

The risk-assessment techniques for technical system can be divided into formal and informal approaches. (Diergardt, 2005) The informal models such as *HAZOP* (Suokas, 1993) and *FMEA* (DoD, 1980) describes the system behavior using tabular approaches or some descriptive language. The formal models refer to the class of models that apply a logical construct to describe the system. They include the classical *Probabilistic Risk Assessment (PRA)* techniques such as the *Event Sequence Diagram (ESD), Event Trees (ETs)* and *the Fault Tree (FT)*. The following is a brief description of aforementioned techniques. More details are included in Appendix D.

ESDs are used to define the context within which various causal factors would be viewed as a hazard, source of risk, or a safety issue. They have been used both qualitatively for the identification of hazards and risk scenarios, as well as quantitatively to find probabilities of risk scenarios (Stamatelatos, 2002).

Other methods closely related to ESDs and used in risk and safety analysis of complex systems are *Event Trees* and *Decision Trees*. Both are inductive logic methods for identifying the various possible outcomes of a given initiating event. The initiating event in a decision tree is typically a particular business or risk acceptance decision, and the various outcomes depend upon subsequent decisions. In risk analysis applications, the initiating event of an event tree is typically a component or subsystem failure, and the subsequent events are determined by the system characteristics

Fault tree (FT) analysis is a technique by which many events that interact to produce other events can be related using simple logical relationships (AND, OR, etc.); these relationships permit a methodical building of a structure that represents the system. Fault tree analysis is the most popular technique used for qualitative and quantitative risk and reliability studies (Henley et al. 1981, Malhotra et al. 1994).

One of the most effective ways of modeling risks associated with technical systems is to use *ESDs* as the first layer of describing system behavior in case of anomalies, and then to provide the more detailed picture of the contributing causes (of the events in the *ESD*) by *FTs*. Since *ESDs* in their most basic form are reducible to binary logic, the combination of *ESDs* and *FTs* can be converted into a *Binary Decision Diagram (BDD)*. A *BDD* is a directed, acyclic graph. It was introduced by Lee (Lee, 1959) and Akers (1978), utilized by Bryant (1987), improved by Rauzy (1993 & 1997), and enhanced in efficiency and accuracy by Sinnamon and Andrews (1997) in the *FT* analysis. The process is depicted in Figure (4.1). This approach of a

BDD-based *ESD-FT* methodology was used in NASA's risk analysis computer code QRAS. (Groen, et al., 2002)

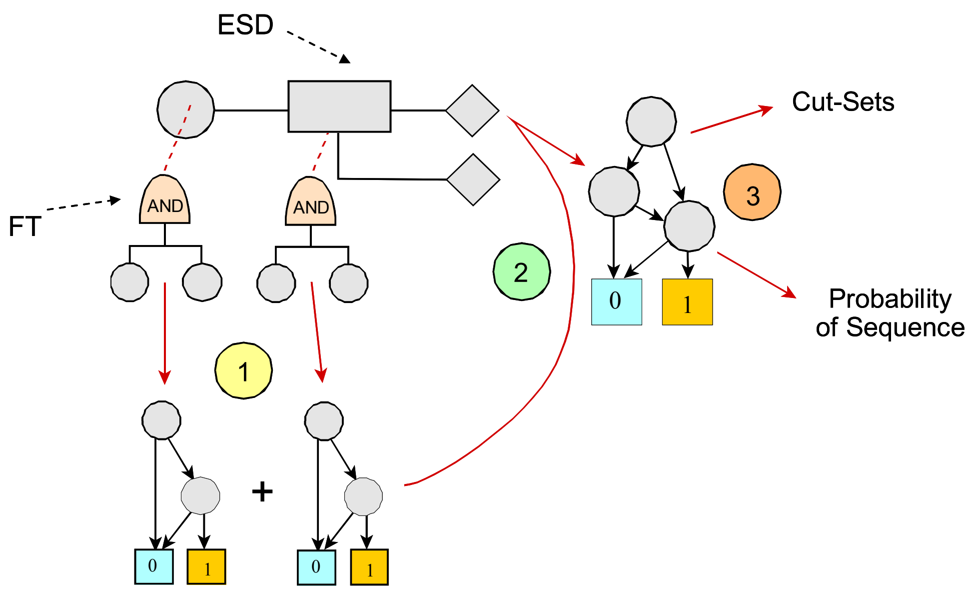

Figure 4.1 Use of BDD to solve combined ESD and FT models (Groen et al., 2002)

More recently and for the case of highly complex technical systems with significant dynamic interactions, simulation-based PRA plat forms (also known as Dynamic PRA (Smidts et al., 2000)) have been introduced (e.g. simPRA, Mosleh at al., 2007). In the simPRA framework, the engineering knowledge of the system, which is reflected in a "planner", is explicitly used to guide the simulation. A "scheduler" would guide the simulation according to the plan, toward events of concern. The simulation creates many accident event sequences and estimates the "end state" probabilities. We refer the reader to Hu (2005) and Zhu (2005) for more detail about dynamic PRA.

4.3 Regression-based Causal Modeling Techniques

Regression-based causal modeling techniques are common in economics and the social sciences. Over the past 20 years, causal modeling (James, Mulaik, & Brett, 1982) has become increasingly popular in organizational psychology. (Jex, 2002) Generally speaking, causal modeling is used in order to distinguish *true* statistical causality from "spurious correlation" (Simon, 1954). The process involves defining a set of variables and their relations, and "testing" all of the relations simultaneously. This is practiced by applying techniques such as "*path analysis*" or "*structural equation modeling* (*SEM*)" (e.g., Bollen, 1989). These techniques show some differences among themselves, but their underlying logic is that the analyst calculates the covariance among the variables in the proposed model (using the actual data) and compares it with the expected covariance (the restriction that the modeler places). This can show how much the model "fits" to the actual data. According to Jex (p.51, 2000) causal modeling is a powerful tool if "the model being tested has a strong theoretical base".

In path analysis, the variables that make up the causal relations are the measured variables (A, B, C, and D in Figure 4.2). In contrast, in *SEM* there are two kinds of variables: measured (observed) and structural (latent) ones. (see Figure (4.3)) Latent variables are hypothetical variables and not measured directly, but they are estimated in the model from a number of measured variables. *SEM* is a combination of path analysis (between latent variables) and factors analysis (between measured variables and latent variables). The principle assumption in these techniques is that the variables that are connected by arcs are *linearly* related.

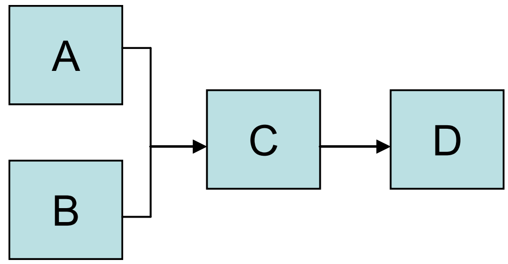

Figure 4.2 Simple path model (Jex, 2000)

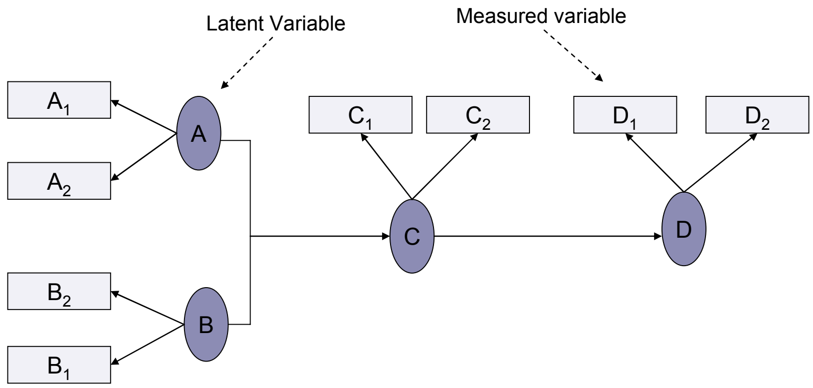

Figure 4.3 SEM with latent and measured varibles (Jex, 2000)

4.4 Process Modeling Techniques

The organizational safety risk theory not only should represent the social aspects of an organization, but also it also needs a technique to model the primary production processes of that organization. Semi-formal techniques have been successfully applied for modeling business processes, because their graphical notation can represent complex system comprehensively. (Diergardt, 2005) Therefore, a semi-formal process technique should be adapted and applied to represent the various processes (e.g., work process) in an organization. Then, for quantification purposes, it needs to be converted to a formal technique that is consistent with other techniques in the framework. Section (4.5.4) describes a conversion approach.

There are different types of semi-formal process modeling techniques in the literature, such as flow chart, state chart diagram, Event driven process chain, (see Diergardt, 2005), Integrated Definition Methodology (Mayer et al., 1995), and *Structured Analysis and Design Technique (SADT)* (Marca and MacGown, 1988; Heins, 1993) . In order to determine an appropriate modeling technique, a few of aspects need to be considered; (1) ease of conversion to a formal technique, (2) ease of communicating the model and results, (3) and generality of the technique for different organization.

SADT is a good candidate because of its consistency with these criteria. *SADT* originated in the field of software and knowledge engineering, and it is also used to model decision making activities. Hale et al. (1997) have adopted this technique for modeling a safety management system.

Figure (4.4) shows the structure of *SADT*. The activity process transmits the inputs (I) to the outputs (O), given the resources (R) and the control/criteria (C). (Hale et al., 1997) The inputs can be information, hardware, raw materials, people, etc. Outputs are the products of the process. Resources are the things, which are needed for performing the activity, such as tools, equipments, and operating individuals. Controls/ criteria include all laws, regulations, and standards that are used to direct and judge the performance of an activity.

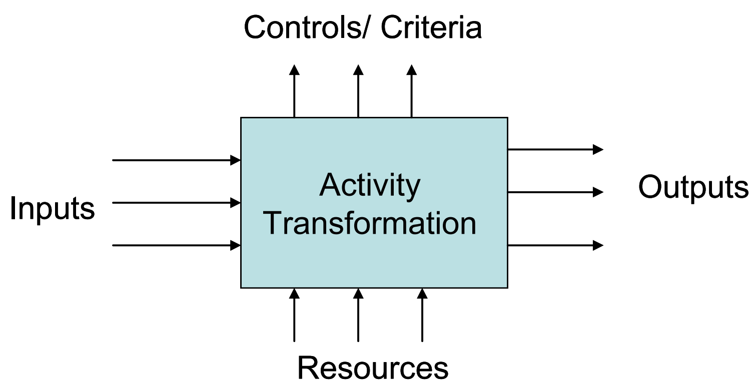

Figure 4.4 Structured Analysis and Design Technique (SADT)

The United States Air Force commissioned the developers of SADT to devise a process modeling method, named IDEFØ, for analyzing and communicating the functional perspective of a system. IDEFØ is a graphical approach similar to SADT with the elements of Input, Control, Output, and Mechanism. (called ICOMs). In December 1993, the Computer Systems Laboratory of the National Institute of Standards and Technology (NIST) released IDEFØ as a standard for Function Modeling in FIPS Publication 183. An IDEFØ represents the whole system as a single activity, named context activity (A0). The context activity is decomposed into detail levels that include its sub-activities. This decomposition process continues to include all relevant process of system. (see Figure (4.5)) (FAA report, 2001)

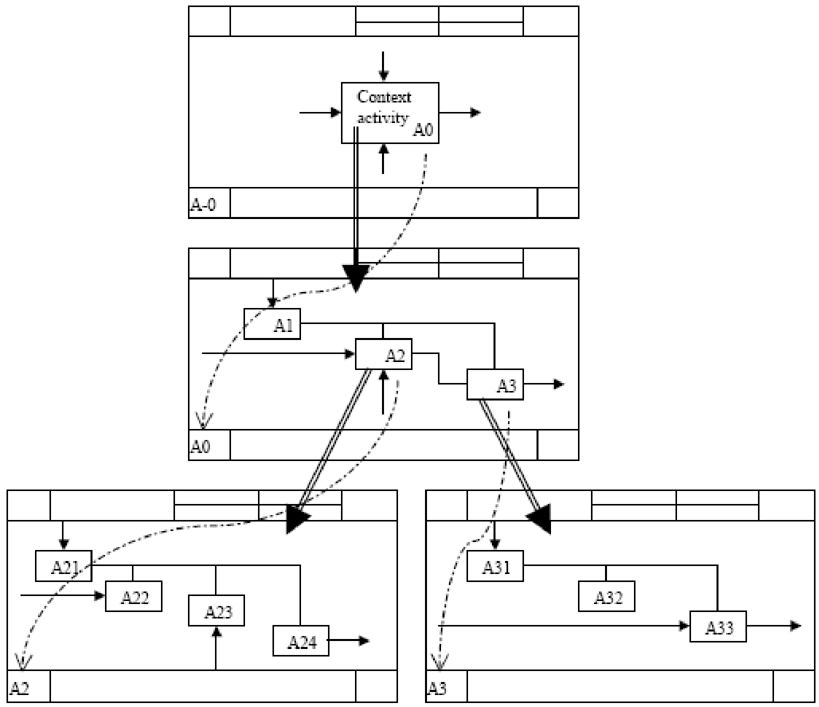

Figure 4.5 A typical decomposition hierarchy in IDEF0 (adapted from FAA report, 2001)

4.5 Converting the Regression-based & Process Modeling Techniques to a Common Technique; Bayesian Belief Net (BBN)

Since an organization is the combination of social and structural aspects, there is a need to integrate the techniques of these two fields in a way they that can feed each other. Process modeling techniques have more mechanistic nature. In contrast, social causal models are more holistic. Thus the common technique should be able to connect these two different natures. We found the *Bayesian Belief Net (BBN)* as a technique that is capable of accepting the integration challenge. In this section, first BBN is briefly introduced (Section 4.5.1), then we explain why BBN is selected as common technique (Section 4.5.2), and finally, it is explained how we can convert regression-based and process modeling techniques to BBN (Section 4.5.3 & 4.5.4).

4.5.1 Bayesian Belief Net (BBN)

A methodology that has gained popularity in recent years to represent causal connections that are "soft", "partial", or "uncertain" in nature is the *influence diagram (ID)* family, particularly the *Bayesian Belief Network (BBN)*. The applications of *BBNs*, also known as *Bayesian Networks, Belief Nets, Causal Nets, or Probability Nets*, have grown enormously over the past twenty years, with theoretical and computational development in many areas. During the 1990s, Bayesian Networks and Decision Graphs attracted a great deal of attention as a framework for artificial intelligence and decision analysis, not only in academic institutions but also in the industry. Recently, due to its power to deal with the soft data in reliability, it has stimulated a strong interest. (Bobbio et al., 1999, Torres-Toledano & Sucar, 1998, and Kim & Seong, 2002)

Bayesian Networks are a network-based framework for representing and analyzing models involving uncertainty. They handle uncertainty in a mathematically rigorous yet efficient and simple way compared with other knowledge-based systems.

A Bayesian Belief Network consists of a set of variables (causes and effects) and a set of directed edges between variables (paths of influence). Each variable has a finite set of mutually exclusive states. The variables together with the directed edges form a directed acyclic graph (DAG). Conditional probabilities carry the strength of the links between the causes and their potential effects. For example for a given state of a variable A with parents $B_1, \ldots, B_n$, we have the conditional probability of the state (A) occurring given the state of the contributing parent nodes: $P(A|B_1, \ldots, B_n)$ (Jensen et al., 1990) (see Figure 4.6). Bayes' theorem in the subjective theory of probability is at the core of the inference engine of *BBNs*.

In the definition of *Bayesian Belief Network*s, the DAG restriction is critical. Feedback cycles are difficult to model quantitatively and no calculus has been developed for causal networks that can cope with feedback cycles in a reasonably general way. More details about *BBNs* are included in Appendix E.

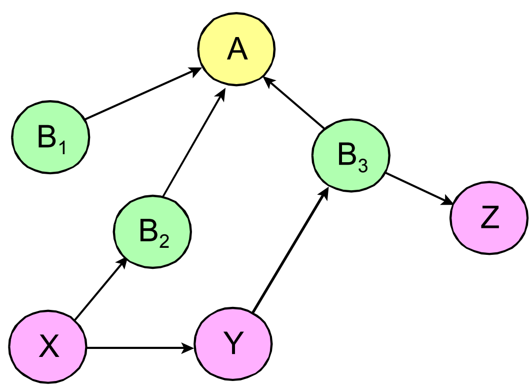

Figure 4.6 A Bayesian Belief Network

4.5.2 Why Bayesian Belief Net (BBN) is Selected as a Common Technique?

There are several reasons for this selection:

1. BBN factors, with a probabilistic nature, can be mathematically linked to the technical system models (e.g., event trees and fault tress). (see Figure (4.7)) This technique is known as Hybrid causal Logic (HCL) (Mosleh et al. (2005))

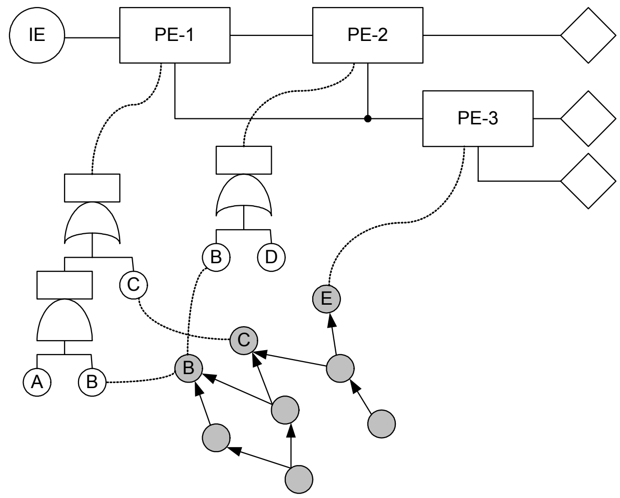

Figure 4.7 Connecting BBN to the technical system techniques (ET & FT) (Mosleh et al., 2005)

2. There are mathematical relations between regression-based techniques and BBN. (Roehrig , 1993 , Burns & Clemen , 1993) (see Section 4.5.3)
3. Most social and psychological theories are in form of regression-based techniques. By establishing the relation between these two techniques, we can include (quantitatively) in a more explicit way the psychological and social theories into the organizational safety risk theory.
4. BBN has the capability of utilizing subjective expert opinions. Adapting this technique makes the quantification of the organizational accident causation theory possible, even with a lack of actual data.
5. On the other hand, regression-based techniques are capable of testing causal theories using actual data. Linking BBNs and regression-based techniques makes testing of the organizational safety risk theories (or at least part of that) possible, at least partially.

6. For risk management purpose, it is necessary to have a technique that is capable of assessing the impacts of potential changes. BBNs can be applied for predicting the effects of changes. (see for example, Anderson and Lenz's (2001) use of BBN for modeling the impact of organizational change)
7. Process modeling techniques are semi-formal quantitative techniques and need to be converted to formal techniques for the purpose of quantification. In Section (4.5.4), we demonstrate how to convert the process modeling technique to BBNs.

4.5.3 The Relation between Regression-based Techniques and BBN

Regression-based techniques are "statistical" techniques rooted in social sciences and economics, while BBN is a "probabilistic" technique rooted in Artificial Intelligence. These two groups of techniques have been used traditionally in quite different areas of application. Path analysis and SEM usually have been applied for testing and understanding the causal relationships. In contrast, BBNs have been used as a method of knowledge representation and as a reasoning framework. However, it can be seen that both methods have the potential of being a "prediction" tool. (Roehrig, 1993) Some references such as Roehrig (1993) and Burns & Clemen (1993) have discussed the mathematical relationships between these two techniques.

The underlying assumption in path analysis and SEM is that the connected variables have linear relationships, but it is possible to incorporate the multiplicative composite of variables as additional variables in the causal model. In addition, path analysis has been traditionally applied to continuous quantities, but most of the underlying theories can be applied to discrete variables as well. Roehrig (1993) has derived the mathematical relation between two techniques, treating a simple causal model, where both nodes can only be true or false. His result showed the following relation: (equation 4.4.)

$$r_{xy} = (\Pr\langle y|x\rangle - \Pr\langle y|-x\rangle)\frac{\sigma_x}{\sigma_y} \qquad \text{(Equation 4.1)}$$

where r_{xy} is the correlation coefficient between X and Y. σ_x and σ_y stands for standard deviation of variable X and Y respectively. Pr (y|x) is the conditional probability of y given x. We refer the readers to Roehrig (1993) for more complex relations in case of multiple causes.

4.5.4 Converting Process Modeling Technique to BBN

We recall that SADT method is an effective approach for representing the process system of an organization. We will show that how SADTs can be converted into a BBN.

IDEF0 is an approach for modeling the system of processes in organization. Looking at the hierarchical structure of IDEF0, two activities in this technique are either sequential or hierarchical. For example, in Figure (4.8), A_2 and A_3 are related sequentially, and A_{22} and A_2 are related hierarchically (A_{22} is a sub-activity of A_2). But in realty, it is possible that an output performance of an organization is the result of two parallel activities, which are neither sequentially nor hierarchically related.

Thus, we recommend the building block in Figure (4.8) for process modeling of organization.

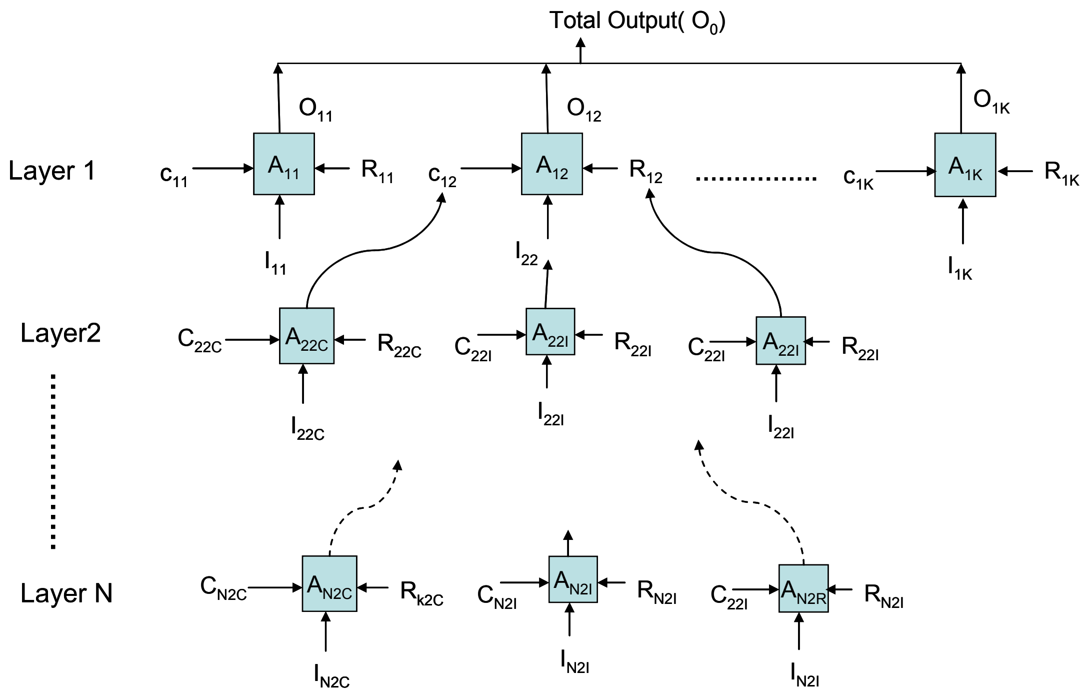

Figure 4.8 Modified process modeling technique

The total output O_0 can be broken down into output O_1 to O_k that are the outputs of parallel activities A_{11} to A_{1k} . Each of these activities (based on SADT technique) have their own Resource (R), Input (I) and Control/Criteria (C). The second layer of activities, comprise those that have R, I, and C of the layer one as their outputs. For example, R_{12} is the resource for activity A_{12} and the output of activity A_{22R} ; I_{12} is the input of activity A_{12} and the output of activity A_{22I} **;**and C_{12} is the control for activity A_{12} and the output of activity $A_{22C.}$

The same logic will hold for the activities from layer 1 to layer N (the layer where the modeler stops decomposition). Figure (4.8) shows a schematic process model for organization. The process model can become more complex in several ways:

- It is possible that some supporting activities in the second layer, for example, are common between two parallel activities in the first layer.
- It is possible that some I, R, C are common between two parallel activities.
- It is possible that more than one activity support the elements in the higher level. For example, C_{12} can be supported by a couple of activities parallel to A_{22C}

This $K\times N$ process modeling technique can be converted to BBN as shown in Figure (4.13).

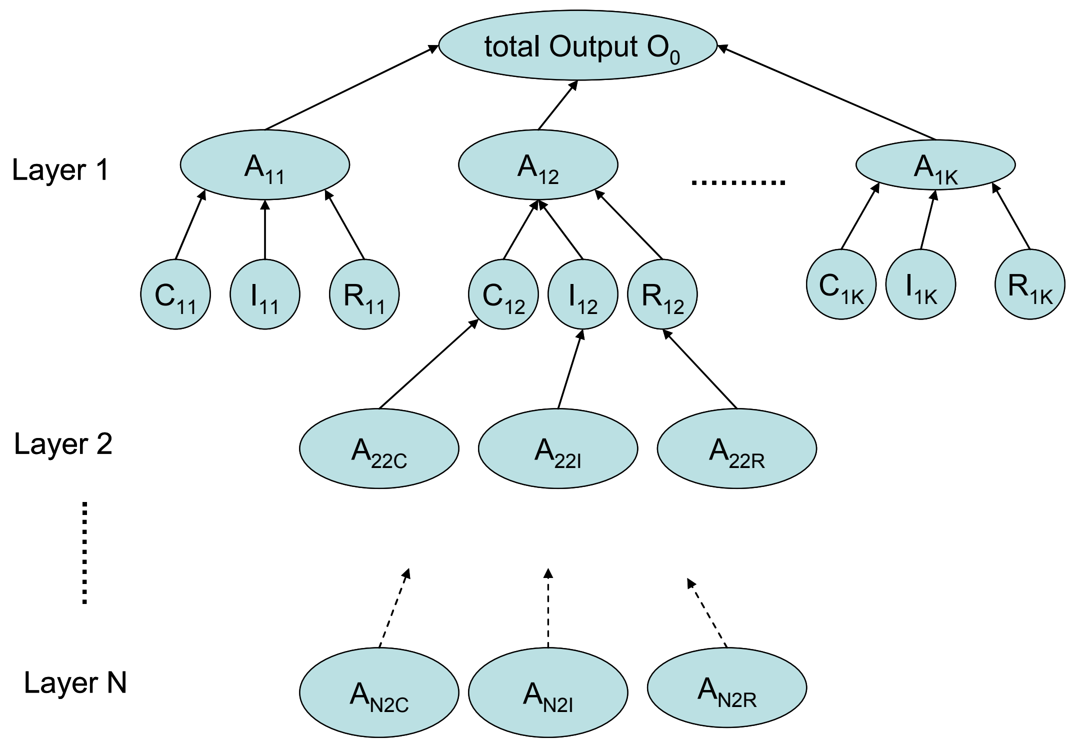

Figure 4.9 The conversion of process modeling technique to BBN

In Figure (4.10) the quality of output would be a function of the quality of activities A_1 to A_k . Knowing the state of A_1 to A_k as well as the conditional probabilities for O_0 given A_1 to A_k , we can reach the probability of output with specific state. For example, considering a binary state for the factor (success and failure), by knowing the probability of success and failure for activities in layer N, and also the conditional probabilities, one can find the probability of total output being in the success state.

4.6 Integrating the Configurational Characteristic

As we mentioned in Section (3.2.3), one of the challenges in the modeling organizational behavior pertains to the "combinational effects" of the factors. Searching for a technique that can capture this characteristic, we found that the so-called *configurational* approach, a good candidate. Configuration is defined as "conceptually distinct characteristics that commonly occur together" (Meyer et al., 1993, p.1175). Schulte et al. (2006, p.648) believe that configurations "allow for examining multiple characteristics simultaneously while accounting for the interrelationships and interactions among them".

Configuarational approaches have been applied to different areas of organizational research, such as organizational structure and strategy (Doety, 1993), Human Resource Management (HRM) (e.g., Delery & Doty, 1996) and climate (Schulte et al., 2006). The logic behind all these studies is the characterization of a unit or organization based on patterns or profiles of different factors, instead of analyzing them independently. For example, in HRM, the idea is that "different HRM practices are interrelated and interact as a system in achieving their effects. Examining single practice or sets of practices simultaneously in a regression does not allow for capturing complementary effects and interrelations among the practices. Only by examining configurations across all practices we can determine whether the entire system of practices, taken together, explains more than the sum of the effects of the individual practices" (Schulte et al., 2006, p.648)

Doty et al.(1993) have utilized two configurational theories including Mintzberg's (1983) theory of organizational structure and Miles and Snow's (1978) theory of strategy, structure, and process. Mintzberg defined a set of design factors (including the key coordination mechanism, the key part of the organization, the type and degree of centralization, formalization, specialization, and hierarchy) and contextual factors (including the organization's age and size, attributes of its environment, and technology). He also identified five ideal-types of organizations (including simple structure, machine bureaucracy, professional bureaucracy, divisionalized form, and adhocracy), each as a unique combination of organizational design and context. For example, a simple structure organization is highly centralized and is directly supervised. The ideal organization for this structure, with respect to age and size, is a small and young organization. The ideal context, on the other hand, is an unsophisticated, non-regulating technology in a simple and dynamic environment.

Some other research (e.g., Schulte et al., 2006) has used *cluster analysis* techniques to identify configurations and types. There are different *cluster* analyses approaches, but all apply the same philosophy to distinguish the types. First, the entities are assessed on a set of variables, and the profiles of their scores are obtained. Second, the similarity of each profile to all other profiles is estimated, using similarity metric (e.g., distance metric, correlation coefficient). Third, decision rules are applied to similarity scores in order to determine the similar profiles that can be merged together into a "type". (Mumford & Espejo, 2007) The most common decision algorithms are: single linkage, complete linkage, average linkage, and centroid. (See Ghanadesikan, et al., 1989 for more detail)

As we will see in Chapter 5, in the organizational safety risk framework, different factors such as safety climate, safety culture, organizational safety practices and their related sub-dimensions interact and are interrelated in non-linear ways. Rather than quantifying all possible interactions among factors and sub-dimensions, *configurational* approach can capture these interactions in an easier way.

The following describes how we can use the *configurational* approach to operationalize part of a theory. Assume that part of a model has factor A as a predictor of factor C. (Figure (4.10)) Factor A and C include four interrelated sub-factors or dimensions, and there are some interrelations between factors A and C. Instead of quantifying the sub-relations between the factors, using the *configurational* approach, we determine the relation between the type (profile) of factor A and factor C. The underlying concept is that the type of factor A predicts the type of factor C.

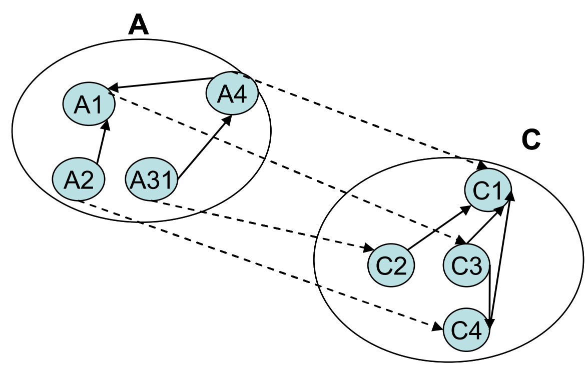

Figure 4.10 Adapting configurational approach

As a first step, we need to use data from ideally a large number of organization, and by applying cluster analysis, find possible types (configuration) for factors A and C. The values of sub-dimensions for each category are defined as average values in each type. For example, X_{11} is the average value of factor A1 in the configuration number 1. Table (4.1) shows a typical empirical profile of configuration for factor A .

Table 4.1 An example of configurations with respect to factor A

Configuration Number	A1	A2	A3	A4
1	X_{11}	X_{12}	X_{13}	X_{14}
2	X_{21}	X_{22}	X_{23}	X_{24}
3	X_{31}	X_{32}	X_{33}	X_{34}
4	X_{41}	X_{42}	X_{43}	X_{44}

The second step is to define the value of fit for each organization with respect to each category. The analyst can use the deviation score (Delery & Doty, 1996, Doty et al., 1993) in order to assess the fit between the profile of each configuration and the empirical profile of the organizations in the sample.

As the third step, the analyst can assess to what extent the fit to a specific type of factor A can predict the fit to a specific type of factor C, using regression-based model. The estimated values from the regression-based model can be translated to a BBN model (describe in Section 4.5.3). In the BBN context we are concerned about the conditional probability of having specific type of factor C, given a particular type of factor A.

In order to assess the effects of change in this model, we need to consider the effect of change in a system of factors (from a configural perspective), instead of a single factor. Since the configurations are defined as "characteristics that commonly occur together" (Mayer, et al., 1993, p.1175), it is reasonable to consider the change form one configuration to another, instead of assessing the effects of change in a single factor. For example, in Figure (4.14), the analyst can assess the effect of change in factor A from type 1 to type 2, instead of analyzing the effects of change in factor A1.

The effects of change in organizational factors should be viewed systematically, instead of individually. From their study, Schulte et al., (2006) suggest that "changing single aspects of the work environment, without attention to other related dimensions, may have unintended negative effects on the individuals' attitudes." By applying a *configural* approach, decision makers can examine the effects of different patterns of organizational factors and find the most appropriate pattern.

4.7 Integrating Subjective Qualitative Data in BBN

As mentioned in Section (4.5.1), one of the significant aspects of *BBN* method is its use of subjective data. In some part of the model, it may be hard to find data, and the modelers may want to consider the expert's knowledge or the qualitative knowledge based on theory. For example, based on Figure (4-15), theorists know that it is highly probable that a "high" quality factor C leads to "high" quality factor D, or it is highly probable that a specific type of factor A, leads to specific type of factor B and E. (see Figure 4.11) In such cases, there is a need for a method, capable of dealing with qualitative data without assigning them numerical values. The *Qualitative-Quantitative Bayesian Belief Network (QQ-BBN)* (Wang, 2007) provides a solution for this case. According to this approach the deeper parts of the BBN which are farther from direct observation are assessed using a qualitative scale (e.g., High, Medium, and Low) for likelihoods and conditional likelihoods. A qualitative likelihood "calculus" caries the inference from such deeper layers of the network to points where observation based assessments of probabilities are possible, or where the experts feel more comfortable expressing their beliefs in a numerical scale. This approach, however, requires a linkage between the two scales at the boundary between the qualitative and quantitative parts (see Wang, 2007 for more detail).

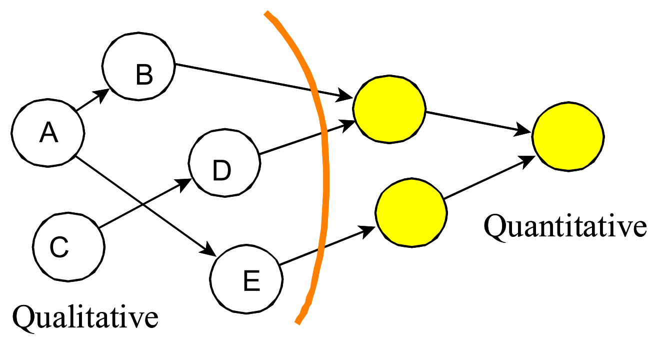

Figure 4.11 Qualitative-Quantitative BBN concept (Wang, 2007)

4.8 Integrating Deterministic & Dynamic Characteristics

In Section (4.5.4), we described how to convert the semi-formal *process modeling* technique to a formal technique, BBN, for quantification purposes. In cases where the modeler does not have a detailed deterministic relation between two factors, probabilistic techniques such as BBN are preferred. But, modelers may have enough information about the interactions of factors for some parts of the model to allow the use of deterministic techniques. The deterministic modeling technique can be either analytical or simulation-based. Simulation-based techniques such Agent-Based Modeling (ABM) (e.g., Wooldrige, 2002) and System Dynamics (SD) (e.g., Sterman, 2000) usually are the only solution if the formal model is complex and analytical solution is not possible or too time-consuming.

As sterman (2000, p. vii) explains: “System dynamics is a perspective and set of conceptual tools that enable us to understand the structure and dynamics of complex systems. System dynamics is also a rigorous modeling method that enables us to build formal computer simulations of complex systems and use them to design more effective policies and organizations”.

System dynamics show significant capabilities for modeling certain human behavior and decision making processes, and as such is a good technique for modeling aspects of organizational behavior. It was developed initially with the intention to study the behavior of industrial systems to show the way policies, delays and structures are related and how they influence the stability of the system. As J.W. Forrester (1961) explains “It [*system dynamics*] integrates the separate functional areas of management, marketing, investment, research, personnel, production, and accounting. Each of these functions is reduced to a common basis by recognizing that any economic or corporate activity consists of flows of money, orders, materials, personnel, and capital equipment” (p.vii).

System Dynamics strength also lays in its ability in accounting for nonlinearity in dynamics, feedback, and time delays. This technique is a combination of qualitative and quantitative tools, and it simulates the feedback loops. (see Figure 4.12)

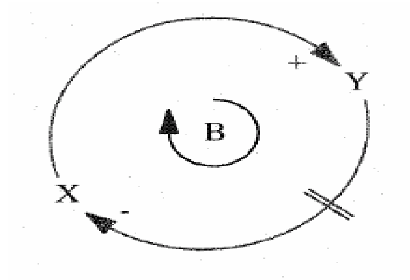

Figure 4.12 Causal loop diagram

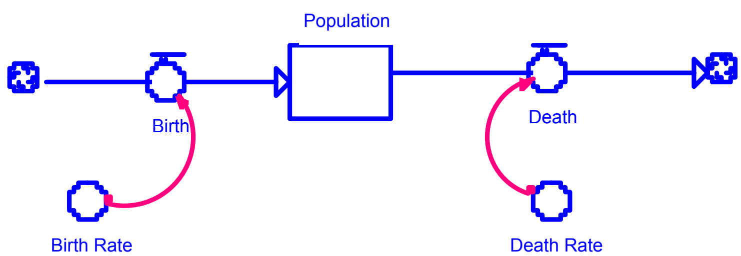

Figure 4.13 Stock and flow diagram

The quantification of *system dynamics* models is done with the help of "*stock and flow diagrams*" (Figure 4.13). *Stock* (population in Figure (4.13)) represents accumulation of some measurable entities (e.g., people, parts, money, or even intangibles such as happiness. (Ford, 1999) that are the in the same state. *Stocks* characterize the state of the system and generate the information upon which decisions and actions are based (Sterman 2000). It changes with an inflow or an outflow. *Flows* (birth and death in figure (Figure 4.13) are the physical or conceptual entities that leave the system state and move over time. Auxiliaries (birth rate and death rate in Figure (4.13)) help to "describe the flow" (Ford, 1999, p.19).

Mathematically, a System Dynamics model represents a system of differential equations as represented in Equation (4.5):

$$\dot{X} = f[x(t), u(t), t]$$
$$Y(t) = g[x(t), u(t), t] \qquad \text{(Equation. 4.2)}$$

Here u (t) stands for the vector input variables, Y (t) is the vector of output variables and X (t) the state variables.

4.9 Adapting a Human Reliability Technique

As Rasmussen (1997) mentioned, human error assessment has moved from deviation-based models (e.g., *THERP* (Technique for Human Error Rate Prediction) Swain & Guttmann, 1983) to the cognitive-based operator model (e.g., Mosleh & Chang, 2004). Here we do not intend to provide an assessment of human error modeling methods and refer the readers to several representative papers in the literature (e.g. Mosleh & Chang, 2004). However, since the human performance model is part of the organizational performance model, some generic principles are highlighted here.

As we mentioned in Section (3.2.3), the philosophy of the modeling human factor should be based on the combinational effects of the influencing factors. The categorical approach to modeling organizations has been applied by some researchers to attempt for some human "*performance shaping factors*". For example, Aronoff &

Wilson (1985) describe comprehensive configurations of individual and group characteristics. They showed, for example, that some personality types are more congruent with some situational features, such as the group structure, the reward basis in the group, and task difficulty. For example, in their view, affiliation should be moderate when the task is highly complex. But the point is that people and their contexts are not one-dimensional, and therefore the prediction should be based on overall "fit" of individuals and their context. In the climate context, Schulte et al. (2006, p.650) conceptualize *psychological climate* as systems and state that "Individual perceptions may work together in forming an overall climate impression, or *psychological climate* system, for a focal person. In this case, different profiles of multiple climates reflect the different ways that individuals see the entire system of climate".

Using the *configurational* characteristic with *BBN* is recommended for human error modeling, since it provides a way for dealing with dependency of individual performance shaping factors in human reliability analysis. *Cluster* analysis can find the specific profile or pattern across individuals' attributes. For example, individuals can be grouped into categories based on their patterns or profiles across measures of their ability and desires. For instance, one profile might reflect high ability, a strong desire for autonomy, and weak desire for job variety, while another pattern could reflect high ability, strong autonomy and strong job variety desire. Such pattern or configurations can then be correlated with specific human error.

The concept of "error" by an individual member of the organization can be viewed from two different perspectives:

1. It is possible to consider the total performance of an individual as a function of his/her internal performance shaping factors (e.g., motivation) and external performance shaping factors (e.g., complexity of procedures, quality of tools, and resources). Then, the possibility of an individual making an error (unsafe act) could be as function of all his/her internal and external performance shaping factors. (see Figure 4.14)

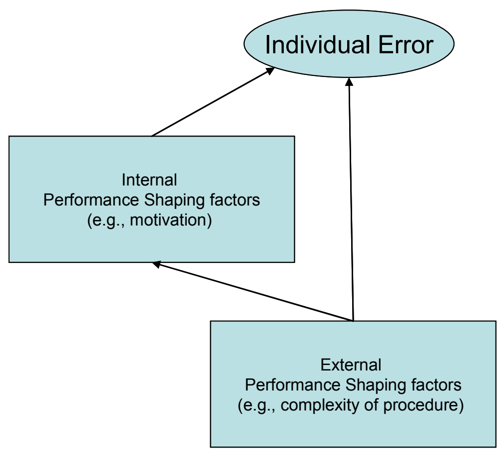

Figure 4.14 Individual error model as a function of internal and external PSFs

2. The other view uses the process modeling technique (mentioned in section 4.4) , expressing the total quality of an activity as a function of an individual action, the quality of tools, resources, and procedures. (see Figure 4.15) In this case the individual error is defined as a deviation of individual from procedure and/or incorrect use of tools and resources (Eghbali and Mandalapu, 2005).

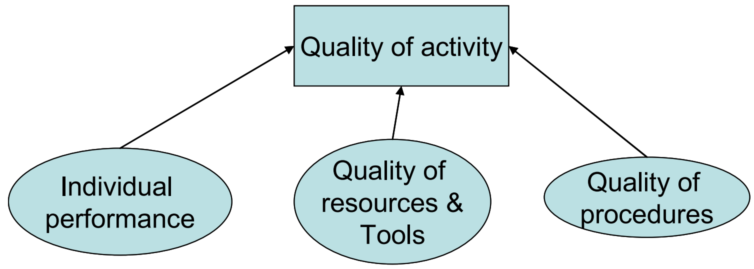

Figure 4.15 Individual error as one of root causes of quality of an activity

The first view is similar to the approach of human reliability analysis (e.g., Mosleh et al. 2004) in order to estimate an individual error. In contrast, in the second view, the concept of human error is close to the quality of human performance. Both of these approaches are correct, but each has its own practical limitations and might be more appropriate for specific objectives.

The limitation of the first view is related to the deficiencies of human reliability methods. Most of these methods are data-driven, and some that are theory-based only cover the theoretical relation between internal performance shaping factors and the human error. The relation between organizational factors (e.g., human resource functions) and internal performance shaping are not adequately modeled. Therefore, using the first perspective for the organizational safety theory is confronted with this challenge.

On the other hand, the second view is more appropriate for models of human resource systems, since the concept of error is close to the concept of the quality of human performance. The challenge of using human resource references for safety causal modeling is that those references mostly focus on the general factors and not on industry-specific factors (Baines et al., 2005).

4.10 Defining the Hybrid Technique for Organizational Safety Risk Framework

Sections (4.2) to (4.10) described different techniques to cover different aspects of an organizational safety risk framework. This leads to the idea of creating a hybrid modeling technique that can capture different dimensions and objectives in a unified, integrated modeling environment. The proposed hybrid modeling includes *risk analysis techniques for technical systems* (ESD/FT methods), *ordinary BBN* or *QQ-BBN* (for *process modeling*, social and behavior effects, *configurational* characteristics), and *stock and flow diagrams* for deterministic relations. The *SD* environment provides a dynamic integration among these different modeling techniques. In other words, different modules with different modeling techniques can have input and output to system dynamic environments at the core, and thus the model can capture feedbacks and delays as well. (see Figure 4.16)

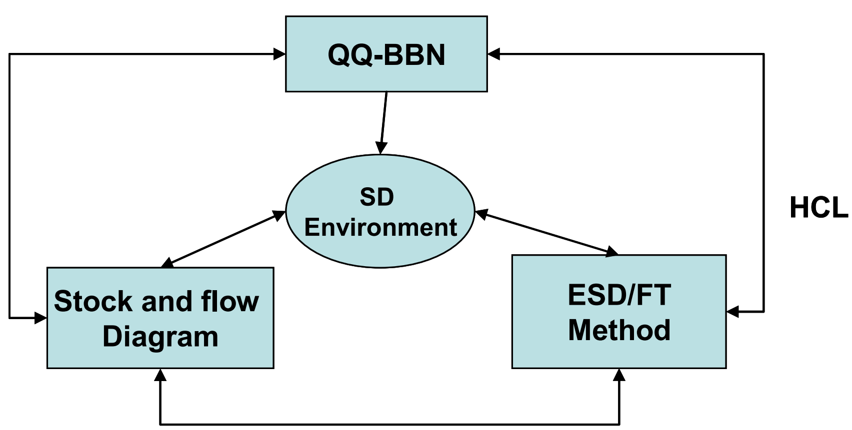

Figure 4.16 Hybrid modeling environment

In this environment, there are three kinds of modeling interfaces: (1) between technical system techniques and *QQ-BBN*, (2) between *QQ-BBN* and *SD*, and (3) between technical system techniques and system dynamics.

The first one, which is the interface of QQ-*BBN* technique with technical system risk, has already been dealt with by the *Hybrid Causal Logic (HCL)*. (Mosleh et al., 2005, Wang, 2007) *HCL* has its roots in the conventional risk analysis techniques used for complex engineered systems, but it has also been extended to facilitate the inclusion of the organizational environment of the physical system. The main layers of the *HCL* are *Event Sequence Diagrams (ESDs), Fault Tress (FT)*, and *Baysian Belief Nets (BBNs)*. *ESDs* on the top (see Figure (4.7)) delineate the possible risk or hazard scenarios. The events, conditions, and causes of the scenarios are incorporated through the *FTs* and *BBNs*, i.e. the second and third layers of the *HCL.* In many cases direct causes of accidents are those system failures or human operational errors that appear as the top events of the fault tress or "target nodes" of *BBNs (or QQ-BBN).* These are usually direct inputs to the *ESD* pivotal and initiating events. Proximate and root causes, including latent hardware failures, latent human errors, and organizational and management effects are modeled through lower layers of FTs and BBNs.

The interface of *SD* with *QQ-BBN* and technical system techniques can be captured with importing and exporting the data from the *system dynamics* environment. *SD* softwares such as STELLA (e.g., Richmond, 2001, Hannon & Ruth, 2001) and Vensim (e.g., Sterman, 2000) have the capability of importing and exporting data. For example, the target node calculated from *BBN* can be imported to

SD and processed inside *SD* (with delays and feedbacks), and also the estimated values from *SD* can be exported to the *BBN* environment. This process can integrate the cyclic nature into *BBN*. The combination of *SD* and *HCL* is illustrated through an example in Chapter 6 of this thesis.

4.11 Measurement Technique: Bayesian Representation for Different Measurement Methods

In this section we describe the Bayesian approaches as an appropriate technique for combination of subjective an objective data. Two advantages are:

- Reduction of uncertainty: this approach integrates two sources of information about the state of a factor (or an attribute), and provides more accurate estimate of the actual state of the factor (or the attribute).
- Possibility of combining subjective and objective information.

Here we describe the Bayesian combination through two cases: (1) for discrete and (2) for continuous measurement variables.

Suppose M_{sub} , M_{obj} , M_{real} stand for subjective measure, objective measure, and real state of "training". For simplicity, we can consider training to have only two states: standard and sub-standard, (for all different kinds of measurement.) The state of "standard(S)" could mean that more than half of the attributes of the factor meet some established standards. The state of "sub- standard ($\overline{S}$)" means less than half of its attributes meet the standards. For example, if subjective measurement of training results in standard (M_{sub}= S), and its objective measurement finds the factor as standard (M_{obj} = S) as well, then the probability of having standard training in reality can be written by applying Bayes theorem as follows:

$$
\begin{aligned}
&P\langle M_{real} = S \mid M_{subj} = S \;\&\; M_{obj} = S\rangle = \\
&\{P\langle M_{obj} = S \mid M_{real} = S\rangle \times P\langle M_{subj} = S \mid M_{real} = S\rangle \times P(M_{real} = S)\} / \\
&\{[P\langle M_{obj} = S \mid M_{real} = S\rangle \times P\langle M_{subj} = S \mid M_{real} = S\rangle \times P(M_{real} = S)] \\
&+ [P\langle M_{subj} = S \mid M_{real} = \overline{S}\rangle \times P\langle M_{obj} = S \mid M_{real} = \overline{S}\rangle \times P(M_{real} = \overline{S})]\}
\end{aligned}
$$

(Equation. 4.3)

$P(M_{real} = S)$ stands for "generic" probability of training being standard, that can be estimated based on historical data, and $P(M_{real} = \overline{S})$ is equal to $(1- P(M_{real} = S))$. $P\langle M_{obj} = S \mid M_{real} = S\rangle$ is the probability that training is objectively assessed as standard , when it is in fact standard. This value is related to the quality of the objective measurement in the organization. The quality of objective measurement depends on quality of "auditing system" and also the quality of "assessor".

On the other hand, $P\langle M_{sub} = S \mid M_{real} = S\rangle$ is the probability that subjective measurement, defined training as standard, given that it is indeed standard in reality. This probability can be related to the accuracy of perception survey and the accuracy of assessors. It also depends on the extent to which organizational members perceive training as standard. Since supervisors function as interpretive filters of organizational practices for organizational members (Ostroff et al., 2003), this probability highly depends on the extent to which supervisors value training in organizations. The same discussion holds for the conditional probabilities given $M_{real} = \overline{S}$.

Now, consider factor F with k attributes (A_i , i=1,…k). Factor F has an actual state (x_i) with respect to attribute A_i. x_i is a continuous value (e.g. between 1-10) that represents to what extent attribute A_i is satisfied in factor F. Each attribute may have two related measures including subjective ($x^*_{i\text{-subj}}$) and objective ($x^*_{i\text{-obj}}$). (Figure 4.17)

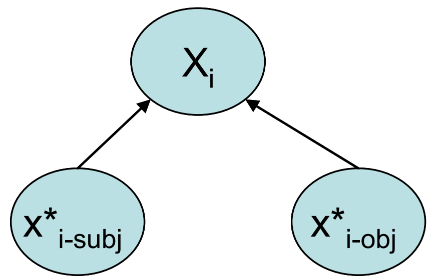

Figure 4.17 Subjective and objective measures of an attribute

Using Bayesian theorem, both kinds of measurements can be treated as evidence to assess the probability of state x_i :

$$\pi\left\langle x_i \middle| x^*_{i\_subj}, x^*_{i\_obj} \right\rangle = \frac{L\left\langle x^*_{i\_subj}, x^*_{i\_obj} \middle| x_i \right\rangle \pi_0(x_i)}{\int L\left\langle x^*_{i\_subj}, x^*_{i\_obj} \middle| x_i \right\rangle \pi_0(x_i) dx_i} \qquad \text{(Equation 4.4)}$$

$\pi_0(x_i)$ = the "prior" state of knowledge about the actual state of factor F with respect to attribute A_i (prior to measuring the factor either objectively or subjectively)

$x^*_{i\text{-subj}}$ = the subjective measure of factor F with respect to attribute A_i

$x^*_{i\text{-obj}}$ = the objective measure of factor F with respect to attribute A_i

$L(x^*_{i\_subj}, x^*_{i\_obj} \mid x_i)$ = the likelihood of having the subjective and objective measures as $x^*_{i\_subj}$ and $x^*_{i\_obj}$, given that the actual state of the factor with respect to A_i is x_i

$\pi(x_i \mid x^*_{i\_subj}, x^*_{i\_obj})$ = the "posterior" state of knowledge about the actual state of factor F with respect to attribute A_i

The next step would be the assessment of $\pi_0(x_i)$ and $L(x^*_{i\_subj}, x^*_{i\_obj} \mid x_i)$ in order to estimate the posterior distribution. It is possible to assume that the subjective and objective measures are independents. For example, the subjective measures are managers' opinions about an attribute, while the objective measure is based on the auditor's observation, and thus these are two independent sources of information. With the assumption of independency, the likelihood function can be written as the product of two likelihood functions:

$$L\left\langle x^*_{i\_subj}, x^*_{i\_obj} \middle| x_i \right\rangle = L\left\langle x^*_{i\_subj} \middle| x_i \right\rangle \times L\left\langle x^*_{i\_obj} \middle| x_i \right\rangle \qquad \text{(Equation 4.5)}$$

$L(x^*_{i\_subj} \mid x_i)$ = the likelihood of having the subjective measures as $x^*_{i\_subj}$ given the actual state of the factor with respect to A_i is x_i

$L(x^*_{i\_obj} \mid x_i)$ = the likelihood of having the objective measures as $x^*_{i\_obj}$ given that the actual state of the factor with respect to A_i is x_i

$L(x^*_{i\_subj} \mid x_i)$ is a measure of the accuracy of the subjective measure, and $L(x^*_{i\_obj} \mid x_i)$ is a measure of the accuracy of objective measure of the factor with respect to A_i. The shape and functional form of the likelihood may differ from one source of data (e.g. informants and records) to another for the same factor. Depending on the type of knowledge about the accuracy of measurements, an appropriate mathematical model (e.g. additive error model, multiplicative error model) should be chosen for a likelihood function. Mosleh & Apostolakis (1984) have discussed several mathematical models for the use of expert opinion. Those techniques are applicable here, since two types of measurements can be treated as two kinds of experts for the same attribute.

For example, if the information available on the accuracy of the measured values is provided in terms of multiplicative factors of the correct answer, a multiplicative error model of the likelihood function is appropriate. Mosleh & Apostolakis (1984) Based on this model, the likelihood functions $L(x^*_{i\_subj} \mid x_i)$ and

$L(x^{*}_{i\_obj} \mid x_i)$ are lognormal distributions with median x_i and standard deviation σ_{i_subj} and σ_{i_obj} respectively, and if $\pi_0(x_i)$ is also lognormal with median x_{i0} and standard deviation σ_{i0} , then the posterior distribution is lognormal with median (x_{ip}):

$$x_{ip} = (x_{i0})^{w_{i0}} (x^{*}_{i\_subj})^{w_{i\_subj}} (x^{*}_{i\_obj})^{w_{i\_obj}} \qquad \text{(Equation4.6)}$$

In the Equation (4.6), both objective ($x^{*}_{i\_subj}$) and subjective measurement ($x^{*}_{i\_subj}$)need to be in the same scale (e.g. between 1-7) , and they provide the same scale for x_{ip} .

$$\pi\left\langle x_i \middle| x^{*}_{i\_subj}, x^{*}_{i\_obj} \right\rangle = \frac{1}{\sqrt{2\pi}(\sigma_{ip})x_i} \exp\left[-\frac{1}{2}\left(\frac{\ln x_i - \ln x_{ip}}{\sigma_{ip}} \right)^2 \right] \qquad \text{(Equation4.7)}$$

where (σ_{ip}) is the posterior standard deviation as following:

$$\sigma_{ip}^2 = \left[\frac{1}{\sigma_{i0}^2} + \frac{1}{\sigma_{i\_subj}^2} + \frac{1}{\sigma_{i\_obj}^2} \right]^{-1} \qquad \text{(Equation4.8)}$$

$$w_{i0} + w_{i\_subj} + w_{i\_obj} = 1 \qquad \text{(Equation4.9)}$$

$$w_{i0} = \left[\frac{\sigma_{ip}}{\sigma_{i0}} \right]^2 \qquad \text{(Equation4.10)}$$

$$w_{i\_subj} = \left[\frac{\sigma_{ip}}{\sigma_{i\_subj}} \right]^2 \qquad \text{(Equation4.11)}$$

$$w_{i\_obj} = \left[\frac{\sigma_{ip}}{\sigma_{i\_obj}} \right]^2 \qquad \text{(Equation4.12)}$$

Then, the range of the actual state of factor F with respect to attribute A_i with a 90% confidence level is:

$$x_{ip} \exp(-1.645\sigma_{ip}) \leq x_i \leq x_{ip} \exp(1.645\sigma_{ip})$$

(Equation4.13)

The inverses of variances are the confidence indices for the prior and the likelihood, respectively. Therefore, the weights (w_{i0}, w_{i_subj}, w_{i_obj}) represent the theorist's relative confidences in his/her prior measure and the measures he/she has received from objective and subjective approaches. These confidences are related to:

1. The accuracy of different measurement instruments (auditing system or perception survey)
2. The accuracy of assessors
3. The accuracy of sampling
4. The accuracy of informants (for subjective measurement)
5. The accuracy of organizational records (for objective measurement)
6. The compliance of each measurement method with the type, level and underlying theoretical nature of a specific factor (or the attributes)

Items1 to 4 can be assumed as a global estimate of accuracy (using historical data or expert opinion), or it can be evaluated based on a constructing root-cause model of error. For example, in the case that subjective measure is based on employees' perception, it is said that an individuals' perception of an organizational function not only is affected by the reality of that function, but also is influenced by his/her own value and supervisors' behaviors. (Ostroff et al., 2003) Then, the accuracy of employees' perception is affected by these influencing factors as well.

The accuracy of subjective measurement instruments refers to construct validity and item constructions in surveys (to be discussed later). In contrast, the accuracy of objective measurement instruments refers to the reliability of auditing system.

The prior confidence depends on the availability of historical data (generic data) for that specific factor. In the absence of any prior information, the modeler can assume a prior distribution with very large relative standard deviation.

The discussion about the appropriateness of different measurement methods for specific constructs based on the methods' type, level and theoretical nature is presented later in this section. If the modeler believes that objective measurement is the ideal approach for an attribute and that there is no need for subjective measurement, then he/she sets w_{i_subj} as zero in the Equation (4.8); and in this case we can say that the attribute is measured objectively. Similarly, if the modeler believes that there is no need for objective measurement, then he/she sets w_{i_obj} as zero in the Equation (4-8); and in this case we can say that the attribute is measured subjectively. Any other cases, in which both w_{i_subj} and w_{i_obj} are not zero, are the cases of a "*supplementary combination*" of objective and subjective measurements.

For example, consider the case where the modeler's evaluation leads to the confidence objective measurement of factor F with respect to A_i is likely to be within a factor of 5 on either side of the true value, 90% of the time. Similarly, the modeler made believes with a confidence of 80% that the likely range of error by subjective measurement is anywhere between a factor of 3 smaller to a factor of 3 larger than the actual value. Then, for $\sigma_{\text{i\_obj}}$ the error factor (EF) at 90% confidence is $5\times5=25$, and similarly for $\sigma_{\text{i\_subj}}$ the error factor is $3\times3=9$ at an 80% confidence level. Thus, for a lognormal distribution the standard deviations are as follows:

$$\sigma_{i\_obj}=\frac{\ln EF}{2\times(1.645)}=\frac{\ln 25}{3.29}=0.979$$
$$\sigma_{i\_subj}=\frac{\ln EF}{2\times(1.285)}=\frac{\ln 9}{2.57}=0.855$$

When no prior information is available, very diffuse lognormal distributions can be assumed in such a way that $\sigma_{\text{i0}} \gg \sigma_{\text{i\_subj}}$ and $\sigma_{\text{i0}} \gg \sigma_{\text{i\_obj}}$. In this case, $\left[\frac{1}{\sigma_{i0}^2}\right]\to 0$ and $w_{i0}=\left[\frac{\sigma_{ip}}{\sigma_{i0}}\right]^2\to 0$, therefore:

$$\sigma_{ip}^2=\left[\frac{1}{\sigma_{i\_subj}^2}+\frac{1}{\sigma_{i\_obj}^2}\right]^{-1}=0.41\to\sigma_{ip}=0.64$$
$$w_{i\_subj}=0.567$$
$$w_{i\_obj}=0.433$$
$$x_{ip}=(x_{i\_subj}^*)^{w_{i\_subj}}(x_{i\_obj}^*)^{w_{i\_obj}}=(x_{i\_subj}^*)^{0.433}(x_{i\_obj}^*)^{0.567}$$

The posterior distribution of the actual state of factor F with respect to attribute A_i is:

$$\pi\left\langle x_i \middle| x_{i\_subj}^*, x_{i\_obj}^*\right\rangle=\frac{1}{\sqrt{2\pi}(0.64)x_i}\exp\left[-\frac{1}{2}\left(\frac{\ln x_i-\ln x_{ip}}{0.64}\right)^2\right]$$

The 95 and 5 percentile of this distribution gives us the range of x_i at a 90% confidence level.

The total measure of factor F, named (x), will be an aggregated measure with respect to its all attributes:

$$x = \sum_{i=1}^{k} \omega_i k_i \qquad \sum \omega_i = 1 \qquad \text{(Equation 4.14)}$$

If all x_i's are measured subjectively, it is said that factor F is measured subjectively. Similarly, if all x_i's are measured objectively, it is said that factor F is measured objectively. If some x_i's are measured subjectively and others are measured objectively, then x is a complementary combination of objective and subjective measurements. If all x_i's are measured both objectively and subjectively, then the value of x is a supplementary combination of objective and subjective measurements and should be estimated using the Bayesian approach similar to procedures applied for attributes. But in this case the variable of interest in Bayesian equation is x, the total measure of factor F, instead of x_i .

4.12 Evaluation Techniques

A major challenge in organizational accident theory is the lack of appropriate evaluation techniques. Fahlbruch et al. (2000, p.22) believe that "Traditional validity measures cannot easily be applied to this process". In this section, first, we provide an overview of "evaluation" processes, and discuss the specific challenges in evaluating organizational safety risk framework. In addition, some approaches are proposed to overcome these challenges.

The “evaluation” and “testing” of the model are discussed under the titles of “verification” and “validation” in the literature. A practical perspective is offered by Sterman: “All models are wrong, so no models are valid or verifiable in the sense of establishing their truth. The question facing clients and molders is never whether a model is true but whether it is useful”. (2000, p. 890) In other words, the purpose of evaluation and testing is to find out whether the model is good “enough” to be used for a specific purpose and end objective. There are different definitions for the terms “verification “and “validation”. In the following discussion, we will attempt to develop an evaluation framework that would be more appropriate for organizational performance theories and models (see Figure 4.18).

As Figure (4.18) illustrates, a “theory” is built based on the principles of theory building, and thus an appropriate technique should be adapted in order to “implement” it. As the next step, the model needs to be “validated”. Validation refers to the method(s) of finding out the extent to which the implemented model can predict the safety performance data. If the validation is satisfied, it means the implemented model is good enough to be used, and it is the end of the procedure. But if the validation is not satisfied, then the verification and modification need to be done in an iterative procedure. The failure of validation can be due to inaccurate input data, theory, implementation, objective output data, or any combination of these causes. (see Figure 4.19)

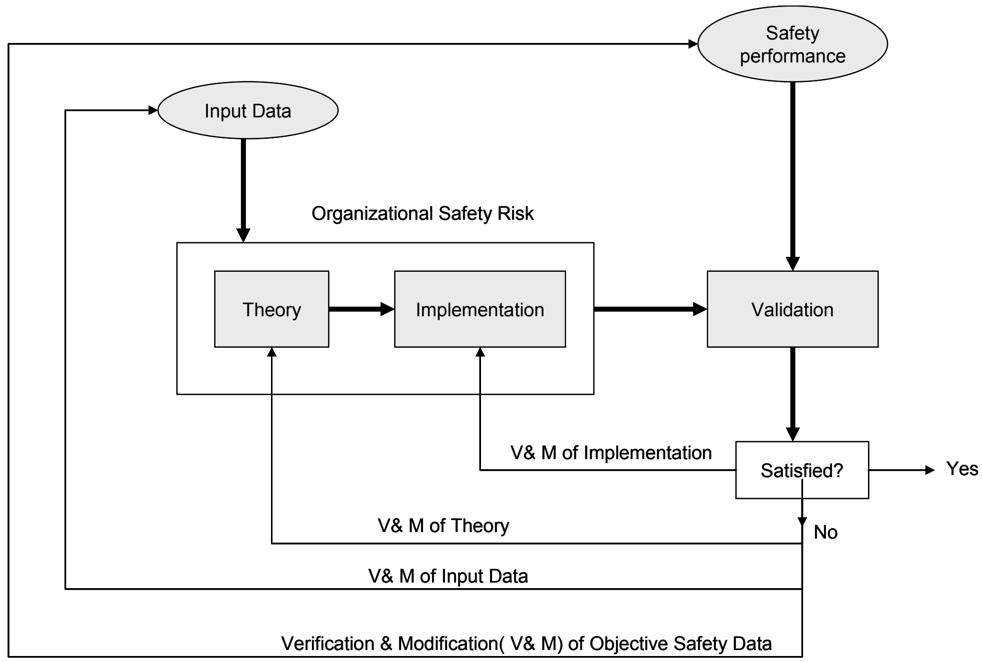

Figure 4.18 Model evaluation procedure

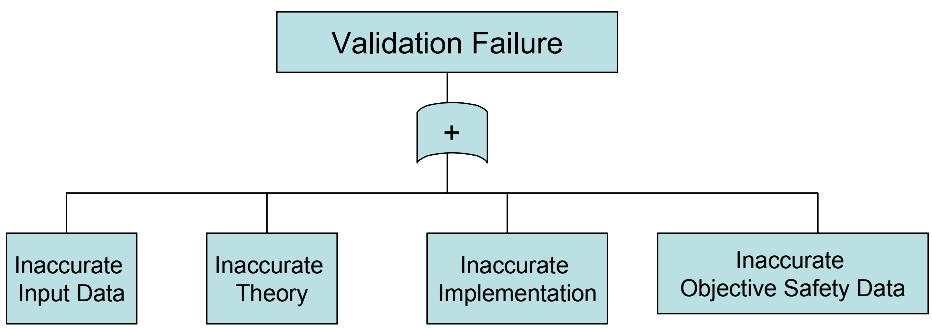

Figure 4.19 The possible causes of validation failure

Thus "Verification" refers to testing the possibility of the occurrences of one of these possible causes or combination of them. Most of the validation and verification tests in the literature refer to one or a combination of these possibilities, but we categorize them in order to avoid missing some of the probable causes and the related verification processes. In addition, classification gives us the opportunity to analyze the challenges of each verification category for safety context and their potential solutions.

There are several possible approaches for the validation part of the "model evaluation procedure". We only propose the approaches that are appropriate for validation of the organizational safety risk model:

Validation (1): Configurational technique

This approach is similar to the method described in section 4.6, but here the modeler tries to find the pattern in all high-level factors (e.g., safety culture, safety climate, etc.) in the model. The researcher should have a sample of organizations and, using cluster analysis try to find the possible types of pattern of high-level factors in the model. Then, the validation would be the extent to which the value of fit to those types can be a predictor of objective safety output. This approach can validate the comprehensiveness of the factors, but can not validate the relations between the factors. For risk management purposes, managers need to know the relations among the factors, because they want to know how to change the organization (from one pattern to the other pattern). In other words, they should know the order and priority of changes in the factors.

Validation (2): Combination of SEM or path analysis with configurational techniques:

As we mentioned in Section (4.3), SEM and path analysis are the tools for testing the models. But since there are many interactions among the factors in the organizational accident model, we can not test all of them simultaneously. Thus, a combination of path analysis and configurational approach is suggested in order to test the relation between high-level factors. First, the modeler should search for different types of profiles for each high-level factor of the model. For example, different types of safety culture, safety climate and safety structure need to be found using samples of different organizations. Then, the values of fitnesses of different organizations with respect to each factor are plugged into a path analysis or SEM, in order to test the model relations.

Validation (3): Behavior reproducing testing (e.g., Sterman, 2000, Galvin, 2002):

If the model (or part f the model) is quantified in the system dynamics environment, then the validation would be running the system dynamic model for some organizations as case studies. The past data of organizations are entered into the model as input data, and the model is run for a period of time to predict the current organizational safety outcome.

Validation (4): Sensitivity Analysis

Sensitivity analysis can highlight the factors that largely affect the output of the model. In the validation phase, sensitivity analysis gives modelers the information about the factors that are more important to be verified accurately.

If the validation is satisfied, it means that none of the possible causes of failure has happened, and the procedure is finished. But if the validation has failed, then the molder needs to try all the following types of verification to find the sources of validation failure:

Verification (1): Input data and objective safety data

This is related to the verification of the measurement methods described in Section 3.3.2. For example, it is the verification of the:

- accuracy of sampling
- reliability of measurement of the instruments and the assessor
- accuracy of informants
- accuracy of organizational records
- compliance of each measurement method with the type, level, and underlying theoretical nature of a specific factor

One of the challenges of data verification for safety model is the case of a new organization and the lack of historical data. In this case, the modeler can use the data from other applications. These soft data involve uncertainties due to the degree of relevance to the organization of interest. They should be approached by Bayesian methods, and the evidence can be implemented using procedures such as weighted posterior, weighted likelihood, and data averaging. The other issue for soft data is expert elicitation and aggregation (e.g., additive models & multiplicative models). (Mosleh & Apostolakis, 1984)

Another difficulty is the case of rare accident organizations and lack of output safety data (i.e. accidents). In this case, it is recommended to observe incidents and precursors (instead of accidents) can provide relevant information. For example, in the case of organization of airlines, instead of relying on aircraft crash, the modeler can use major, but not catastrophic events such as engine failure as an objective safety output. These precursors are basically “more frequent” and “less consequent” events (compared to accidents) in the technical system risk models (Section 4.2). This is the basic idea in developing the scenarios of accidents in the PRA technique in order to estimate the ultimate risk of the system.

The other obstacle is the unreliability of historical data due to the inaccuracy of documentation and reporting system. As Fahlbruch et al. (2000) has indicated: “The analysis of an accident is always a retrospective social reconstruction process, starting with insufficient information about what happened and resulting in inferences about the causes/contributing factors”. A possible solution for this problem is observing the organization in a specific period of time. During this period, an expert team would measure the organizational factors as input data. At the same time, a voluntary reporting system should be established in the organization so that employees can report incidents confidentially. The reports must be in a structured format, describing the problem and also the circumstances surrounding the incidents. In the structured form, participants need to specify the sources of incidents based on a model-based taxonomy of factors, and also other possible sources based on their own opinions. Then, periodically these reports need to be reviewed by risk management expert in order to map the incidents to the possible root causes. With this data gathering approach, it is possible to verify (1) the reliability of input and output data, (2) the comprehensiveness of factors in the theory (this is related to verification of theory), and (3) some causal relations in the theory (this is related to the verification of the theory).

Verification (2): Theory

Theories need to be verified with respect to underlying logical propositions and supporting literature. In addition, they should be verified by "boundary adequacy tests". (e.g., Sterman , 2000). This test verifies the appropriateness of the boundaries with respect to objectives of modeling and the extent to which the external factors (outside the model boundary) have significant impacts on the model parameters.

Verification (3): Implementation

Implementation needs to be verified with respect to two different aspects: (1) the extent to which the techniques are fitted to the theory and (2) the extent to which the techniques are implemented correctly. In Section (4.10), the criteria for adaptation of the appropriate quantification technique are explained. Verification of the quantification technique with respect to the second aspect, to some degree, depends on the type of quantification techniques. But some of the tests are more general such as the dimensional consistency test (e.g., Streman, 2000), extreme condition test (e.g., Sterman, 2000, Galvin, 2002), integration error test (e.g., Streman, 2000), sensitivity analysis, time step testing (e.g., Galvin, 2002) and face validity (e.g., Carson, 2002, Galvin, 2002).

A common approach for verifying quantification techniques is testing the tool on a simple case. Although it is not always possible to generalize the verification of a tool from simple to complex cases, it can be assumed as a partial verification.

5. SOCIO-TECHNICAL RISK ANALYSIS (SoTeRiA)[3] FRAMEWORK

5.1 Introduction

The focus of this chapter is on developing an organizational safety risk analysis framework, named "Socio-Technical Risk Analysis (SoTeRiA) that is the third major contribution of this thesis. The proposed theory, which is a realization of modeling principle described in Chapter 3, is intended to overcome some of the limitations of existing models, mentioned in Chapter 2. In Chapter 6, we will explain which ones of those aspects are improved by this research. In Sections (5.2) to (5.11), we elaborate step by step on building the theory (based on the described principle in Chapter 3) and clarifying its elements. The final Section, (5.12), summarizes the theory and provides a schematic representation covering the entire range from organizational factors up to the technical system risk scenarios.

5.2 Defining the Unknown of Interest

Referring to principle (A), the unknown of interest is organizational safety risk. Although most part of this theory is general and can be applicable to three types of organizational safety performance mentioned in principle (O), here we mainly focus on infrequent and medium size accidents such as aircraft accidents, and very rare and unacceptable accidents such as those in nuclear power plants.

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[3] SoTeRiA is the goddess of safety, and of deliverance and preservation from harm in Greek mythology

5.3 Safety as an Organizational Performance

Based on principle (B), safety is one of the organizational outcomes/performances, thus organizational accident theory should be grounded on the organizational performance model. The theoretical frameworks for organizational effectiveness were reviewed, and the model developed by Ostroff et al. (2003) (Figure (5.1)) was adopted for two key reasons:

First, it considers the theoretical relation between organizational culture, organizational structure/practices, and organizational climate, with specific distinction between culture and climate. Based on principle (G), the comprehensiveness of safety model needs the coverage and integration of the social (e.g. safety culture and climate) and structural (organizational safety structure & practices) aspects of organization that influence safety. Most of the previous safety models focus on either social or structural aspects. But previous researches that have attempted to include these two aspects have not established the theoretical relations between them. Besides, there is no clear distinction between safety culture and safety climate in the safety frameworks, and these two have been used, most of the time, with a verity of definitions and interchangeably. A systematic view of safety culture and safety climate fills an important gap in modeling complex system risk, and therefore, this organizational effectiveness model (Figure (5.1)) that has a theoretical relationship between the two concepts of culture and climate has been adopted to fill this gap.

Second, it is a multi-level framework. Based on principle (D), for the purpose of risk management, a cross-level organizational causation theory that can integrate macro and micro perspectives is needed. Thus, this model, which is a multi-level organizational performance framework, has been adopted and modified for organizational safety risk framework.

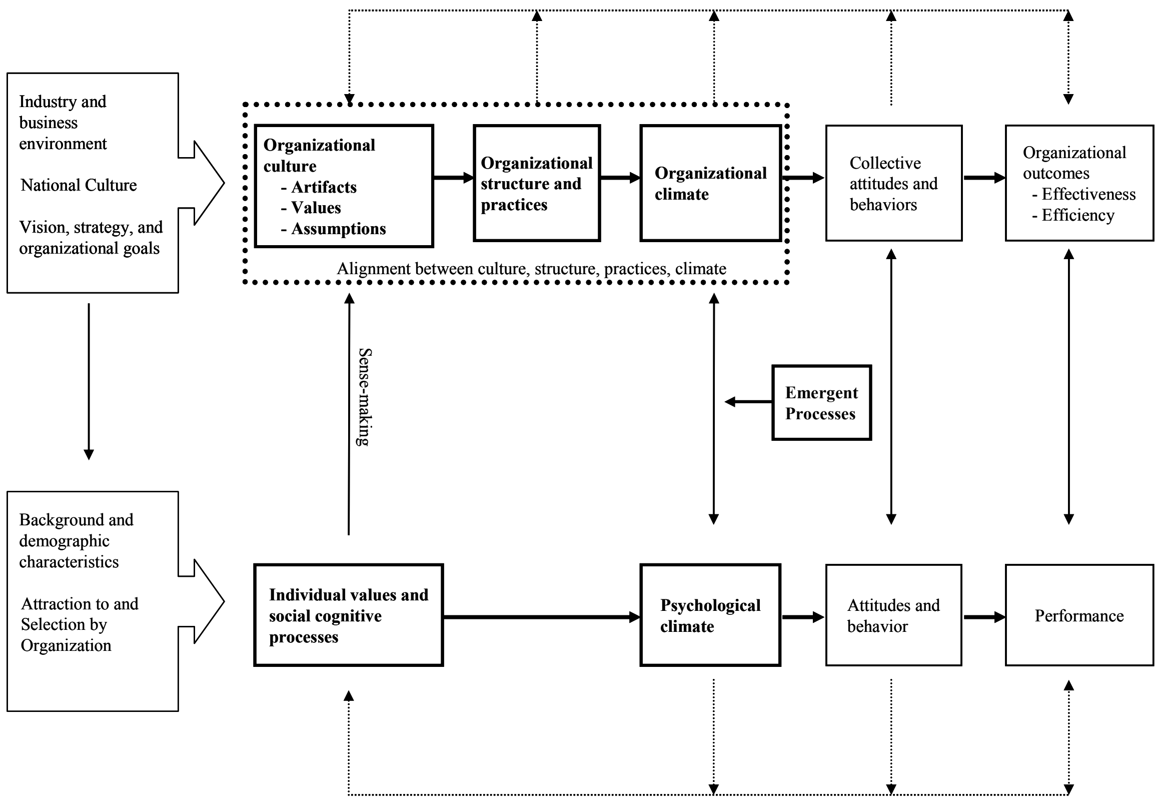

Figure 5.1 Multi-Level model of organizational culture and climate (Ostroff et. al, 2003)

Using this organizational effectiveness model as a basis for organizational safety causal model is reasonable, because safety culture is a sub-facet of organizational culture, and is defined as common safety value in organization (see for example Cooper, 2000, Cox & Cox, 1991). Likewise, safety climate is a sub-facet of organizational climate, and is expressed as shared perception of employees regarding organizational safety practices (e.g. Zohar & Luria, 2005, Griffin & Neal, 2000).

Therefore, we substituted safety culture for organizational culture, safety climate for organizational climate, and safety outcome for organizational outcome to create the multi-level organizational safety causal model. We also added a group level in the model in order to analyze the relations at the group level as well. (see Figure 5.2)

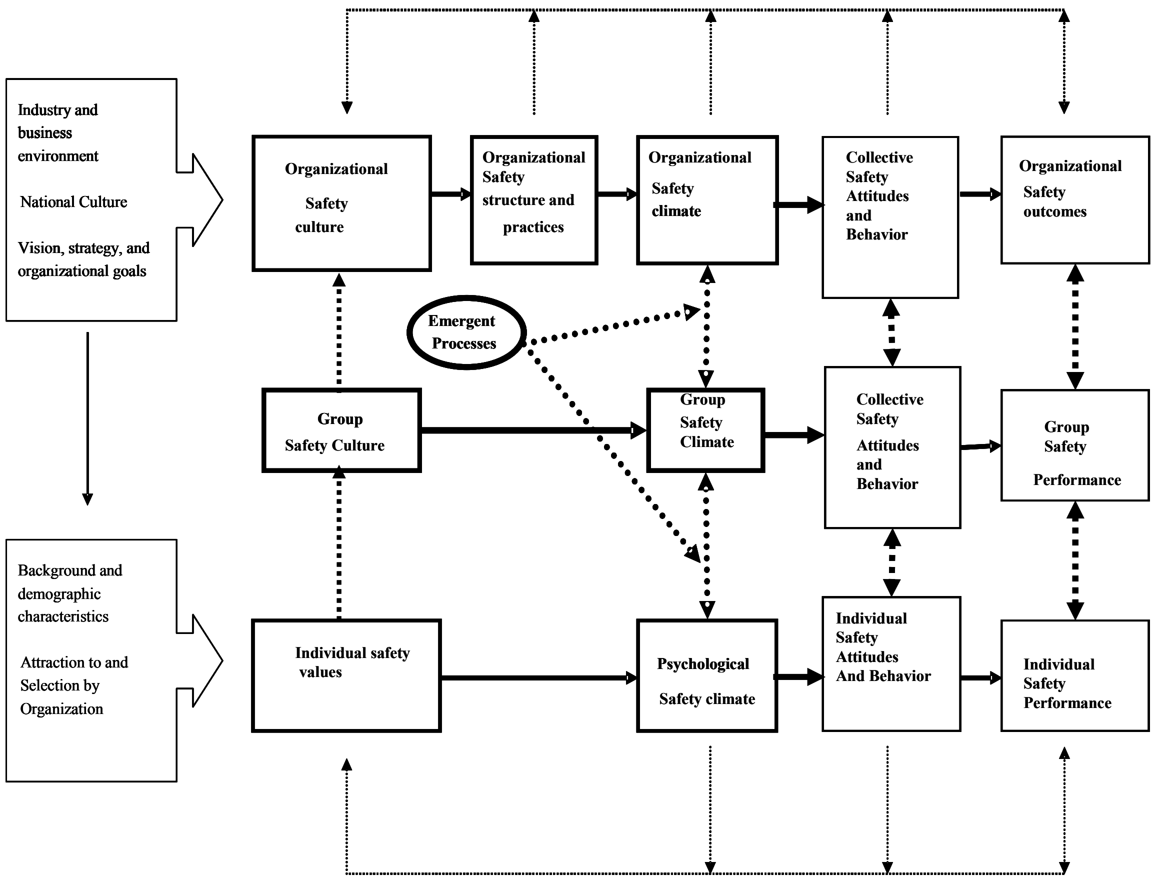

Figure 5.2 Adapting an organizational performance model for safety purpose

5.4 The Interaction of Safety & Other Organizational Performances

Based on principle (B), safety has interaction with other organizational performances. Here, the performance of the organization is divided into safety performance and financial performance that is an important non-safety performance. (see Figure (5.3))

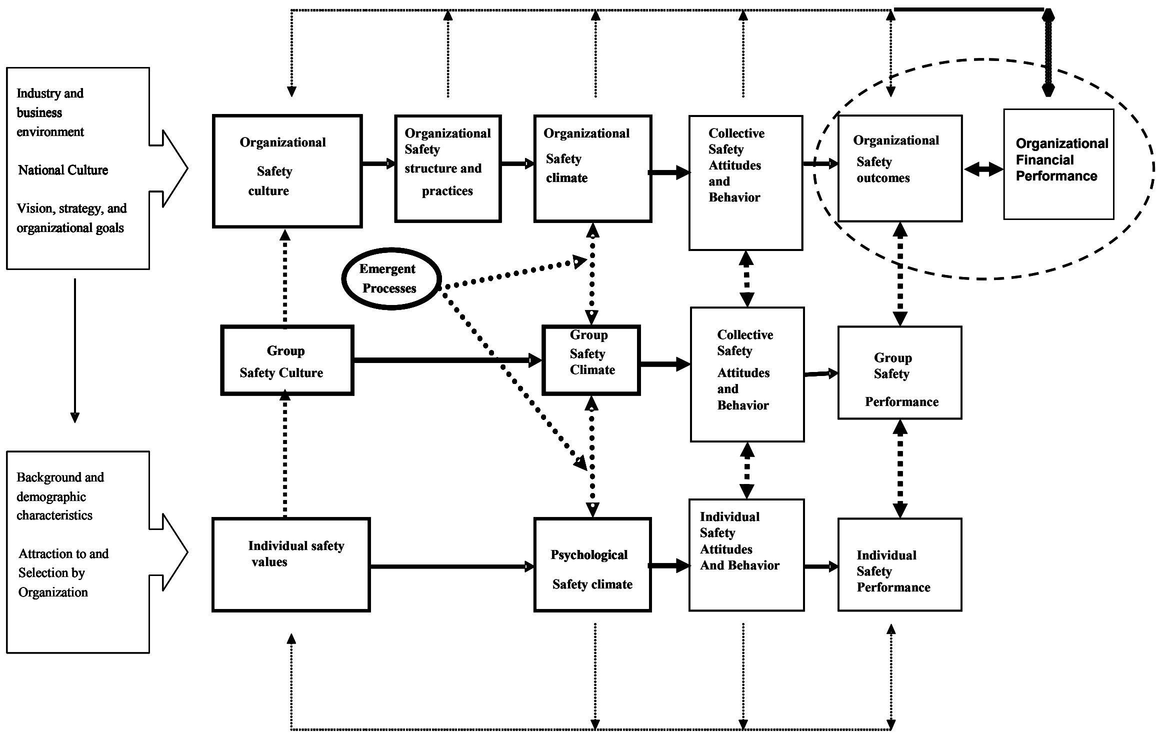

Figure 5.3 The interaction of safety outcome and financial performance

Safety performance impacts financial performance, and financial performance affects safety performance through a number of paths of influence. The financial performance affects the safety performance both directly and indirectly. The indirect effects, for example, would be decisions that a manager makes on training, work environment, operational procedures, etc., based on lack of budget or other distresses. An example of the direct effects is the collapse of morale because of the news on extreme financial distress (e.g. possible bankruptcy). These direct and indirect effects are not necessarily realized in the same period of time. It is possible that an organization is operating perfectly and safety management practices are fine, but due to sharp increase in the oil price, the company moves towards bankruptcy rapidly. On the other hand, safety performance may affect the financial performance directly by internal costs (direct loss of asset as a result of an accident), and indirectly through loss of public confidence, new regulation, and market value, to name only a few parameters.

It can be argued that in high-reliability organizations (e.g. aviation, nuclear power plants) these consequences do not propagate through the organization immediately. There exists an inertia which enables the organization to maintain its stability against financial fluctuations. These barriers or damping mechanisms include:

- Technology Resilience
- Regulation
- High Levels of Professionalism

In the current model (Figure (5.3)), we use safety culture as a barrier that damps the direct effects of financial pressure on the safety practices in organizations. Then, we need a statistical relation between financial pressure and safety culture. Most of the related research has studied the effects of culture on the financial performance (e.g. Siehl and Martin, 1990), not financial performance on the culture. Besides, the investigation of the existence of a possible correlation between financial wellbeing of a firm and the safety performance of firms has been of interest to researchers and managers for a long time. This is particularly important if unsafe operation could translate into a disaster. One of the challenges here is the selection of a suitable set of financial factors and correlating them to safety culture. The preferred method of studying the existence of such a correlation and the degree of its strength however is outside the scope of this thesis and future research needs to be devoted to this topic.

5.5 The Path of Cross-level Analysis

Referring to principle (D), a cross-level safety causal model needs the coverage of paths of influence from the level of organization as a whole, to groups , to individuals, and then from the individual-level back up to organization-level safety outcome. Figure (5.4) shows the path of cross-level analysis in the proposed multi-level framework.

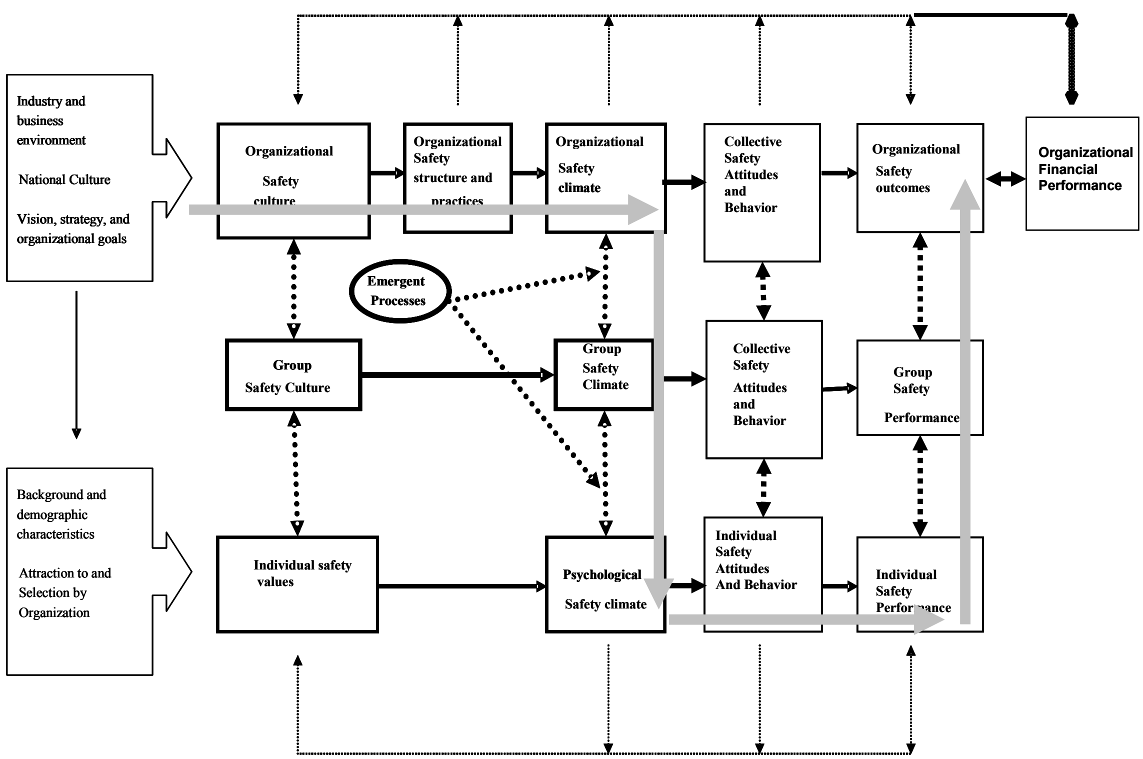

Figure 5.4 The path of a cross-level analysis for organizational accident theory

5.6. Organizational Safety Risk as a Measure of Safety Output Deviation

Based on principle (C), the organizational safety risk is a measure of deviation of organizational safety output from a normative level of safety. Here, we limit the theory to major accidents, and thus the measure of deviation can be the deviation of the technical system from the normative level of safety. Technical system risk (e.g. risk of aircraft crash, risk of core melt in nuclear power plants) can be a measure of deviation from the normative level of safety. Technical system risk, which is substituted as organizational safety output in the Figure (5.4), is a configural construct at the organization level, and emerges from group and individual level performance in a compilation process. Next sections describe this compilation process.

5.7 The Relation between Group Safety Performance and Organizational Safety Output

Organizational safety outcome, which is the technical system risk in this theory, emerges from group and individual performance. Based on principle (L), depending on the nature of emergence, a technique should be used in order to combine the lower-level constructs into the higher-level construct. As we explained in Section (4.2), technical system risk can be represented using logical techniques such as Fault Trees (FT) and Event Sequence Diagrams (ESDs). Thus, these are the candidate techniques that connect the group and individual performance to organizational safety outcome.

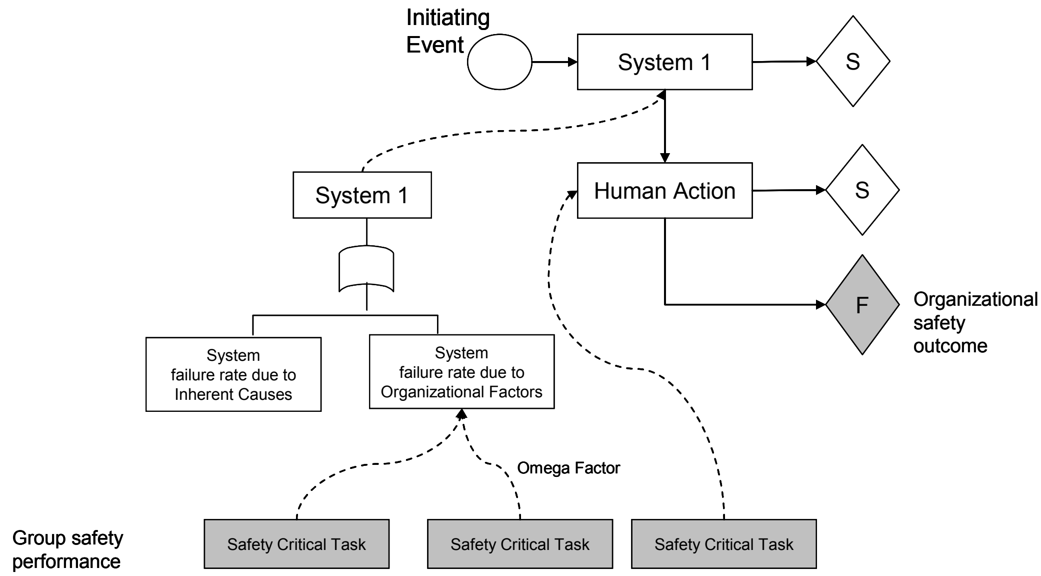

Figure 5.5 The link between group safety performances and organizational safety output

ESDs (see Figure (5.5)) delineate the possible risk or hazard scenarios. The events, conditions, and causes of the scenarios are incorporated through the FTs. In many cases direct causes of accidents are those system failures or human operational errors that appear as the top events of the fault trees. The top events of fault tress (e.g. System 1) are plugged into the ESDs. ESDs represent a set of possible risk scenarios where, given the occurrence of the initiating event, the state of System 1 (a Pivotal Event) determines whether the sequence leads to success (end State S), when it works, or a human action is required, when it fails. Given the success of human action, the final outcome would be success (state S). The failure of Human Action leads to Failure (state F). The failure of System 1 can be due to different types of causalities. One source of system failure can be related to organizational activity that is the concern of this causal theory. The other sources of failure can be related to inherent hardware failure that represents failure mechanisms which are beyond the control of the organization in charge of operating and maintaining the technical system, and for instance it may be related to the manufacturer.

The group or individual performances that have direct effects on the elements of technical system risk scenarios are named Safety Critical Tasks (SCTs). For example, maintenance performance is a safety critical task since it directly affects hardware failure (an element of risk scenarios). In general, SCTs can be either events explicitly specified (e.g. human actions) in the accident scenarios, or implicitly through model parameters (e.g. equipment failure rate). SCTs help to focus on what matters most for safety among many activities in organization.

There can be several SCTs as representations of different group safety performances (e.g. maintenance performance, operation performance). As Figure (5.5) shows the path of connection between group safety performances (SCTs) and organizational safety outcome covers some techniques including FT, ESD, and also Omega Factor (Mosleh & Golfeiz, 1999). The Omega factor technique is a parametric function that converts the nature of group safety performance to the nature of failure rates of the elements of risk scenarios. A more detail explanation about the Omega factor approach can be found in Chapter 5 through the example application.

5.8 The Relation between Individual Safety Performance and Group Safety Performance

The group safety performance, which has been defined as SCT in the previous section, is a configural construct and emerges from individual performances through a compilation process (referring to principle F). Based on principle (H4), depending on the nature of emergence, a technique should be used in order to combine the lower level constructs into the higher level one. As we explained in the principle (P) and also Chapter 4, process modeling technique can model an activity (or a set of activities), and thus we use this technique to model the safety performances of the groups and make a non-linear connection between group members' performances and unit's output performance (SCT). We name this linkage module the "unit process model" in the model. Unit process model includes the direct activities that perform the Safety Critical Tasks (group safety performance).

As Section (4.4) described, the process modeling technique transmits the inputs (I) to the outputs (O) given the resources (R) and the control/criteria (C). The resources may include tools, equipments, and also the individuals performing the task. We make a distinction among the resources and represent any activity as a function of human action, holding at the same time resources to be tools and equipments, and procedures to be a means of control/criteria. As Figure (5.6) shows, unit process model, for example, may include two "direct" activities (i and j)(those in direct relation to technical system) and their "direct" resources, procedures and human actions that make those activities happen. In other words, individuals' safety performances are linked into group safety performance through the process modeling technique. A detail application of the process modeling technique will be described in Chapter 6 through maintenance unit process modeling.

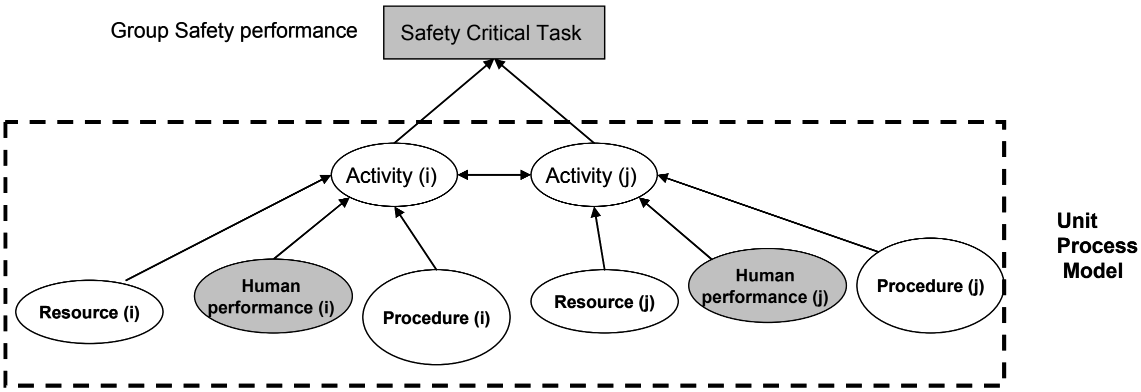

Figure 5.6 The link between individual safety performance and group safety performance

The unit process modeling, presented in Figure (5.6), is a technique to describe how individual performances non-linearly interact with and emerge to the group performance. As Figure (5.3) illustrates, the relation between group and individual performance is a two directional one, meaning that group performance can affect individual performance as well. Most of the effects of higher-level performance (group performance) on individual performance would be indirect. For example, when the unit or organization is performing well, it increases individual's motivation, confidence, and the desire to do well, which in turn is likely to influence individual performance. But there could be some direct link as well; for example, if the group is very cohesive and works interdependently, with members helping one another, then the group performance could then influence the individual's performance.

The rest of the framework will describe how the organizational factors affect the SCTs through their effects on the direct resources, procedures and individuals' performances in the unit process model.

5.9 Safety Culture, Safety Structure/ Practices, Safety Climate, and Their Relationships

5.9.1 Safety Culture

5.9.1.1. Definition

There is some confusion and contradictions about the meaning of safety culture among the safety community. Most of these ambiguities are due to the lack of a clear definition of safety culture, overlap of safety culture and climate, and inadequate multi-level studies of these concepts. In order to clarify what we mean by safety culture, we start by viewing safety culture as a subset of organizational culture.

The concept of organizational culture has become a booming research paradigm after three best-selling books: Ouchi's (1981) *Theory Z: How American Business Can Meet the Japanese Challenge*; Deal and Kennedy's (1982) *Corporate Cultures: The Rites and Rituals of Corporate Life*; and Peters and Waterman's (1982) *In search of Excellence*. The main concern of theses books is to emphasize the strong relationship between organizational culture and organizational effectiveness. Since 1982 many researchers have studied the impacts of organizational culture on different aspects such as effectiveness of a total quality management program (Tata & Prasad, 1998) and technical innovation (Delisi, 1990).

Still, because of the interdisciplinary nature of this concept, a variety of meanings is prevalent among different disciplines such as sociology, psychology, and anthropology. However, as Hofstede, Neuijen , Ohaya, and Sanders (1990) have introduced , there are several commonalities among these various definitions. These commonalities include viewing organizational culture as (1) having multiple layers and aspects (i.e. cognitive and symbolic ones) of organizational circumstances, (2) being a socially constructed phenomenon affected by historical and spatial boundaries, and (3) being a "shared" construct.

Based on Ostroff et al. (2003) opinion, the definition offered by Schein (1992) most comprehensively integrates these key commonalities. Schein (1992) defines culture as:

> "*A pattern of shared basic assumptions that the group learned as it solved its problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems*"(p.12)

Schein (1992) proposed three fundamental layers for any given culture, including observable artifacts, espoused values, and basic underlying assumptions. Observable artifacts are visible organizational characteristics including its "symbols" (e.g. performance and functions), "organizational language" (e.g. gestures, metaphors), "narratives" (e.g. stories, legends), and "practices" (e.g. rituals, ceremonies). (Trice and Beyer, 1993) Espoused values are the values "endorsed by management, and in contrast enacted values are those converted into employee behavior" (Ostroff et al., 2003, p.568). Basic assumptions are deep and unobservable assumptions that over time turn to values.

Although the concept of safety culture is akin to that of organizational culture, the term "safety culture" originated after the Chernobyl nuclear power plant accident in 1986. After this disaster, the International Nuclear Safety Advisory Group

(INSAG) of the International Atomic Agency described that the most probable cause as “poor safety culture” (Cox & Flin, 1998). International Nuclear Safety Advisory Group (INSAG, 1991) proposed that “Safety culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receives the attention warranted by their significance”. The term rapidly spread to the other industries such as chemical processing and commercial aviation, and thus several definitions of safety culture have appeared in the literature. According to James Reason, “the safety culture of an organization is the product of individual and group values, attitudes, competencies, and patterns of behavior that determine the commitment to, and the style and proficiency of, an organization’s health and safety program” (Reason, 1997, p.194). In the aviation industry, Wiegmann and his colleagues describe safety culture as “the enduring value and priority placed on worker and public safety by everyone in every group at every level of an organization. It refers to the extent to which individuals and groups will commit to personal responsibility for safety, act to preserve, enhance and communicate safety concerns, strive to actively learn, adapt and modify (both individual and organizational) behavior based on lessons learned from mistakes, and be rewarded in a manner consistent with these values.” (2002, p.8)

Despite the variety of definitions of “safety culture” in different industries and by different researchers, this concept as such has the notion of organizational culture as its parent and the various definitions share the same three commonalities (mentioned by Hoffstede, Neuijen , Ohaya, and Sanders) among different organizational culture definitions. Therefore, we borrow Schein's definition of culture and adapt it for safety, as following:

> Safety culture is a pattern of shared basic assumptions that the group learned as it solved its safety problems (external and internal), that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those safety problems.

This is a broader definition than previous ones, and has Schein's formulation as its parent. It clearly refers to three layers of safety culture including observable artifacts, espoused values, and basic underlying assumptions. Relying on a well-founded definition of culture helps to avoid some industry specific contents of safety culture.

There is not enough research on the antecedents of safety culture, and not even on organizational culture. Ostroff, et.al (2003) based on the results of other researchers have found that enterprise environment (market characteristics, nature of industry, ownership or control, resource availability, and socio-cultural dimensions), industry and business environment, as well as organization senior leaders' visions and behaviors can be viewed as antecedents of organizational culture. Thus, we have adopted this view point , as shown in Figure (5.3).

5.9.1.2. The Elements of Safety Culture

The next challenge is to identify the elements of safety culture. To date, there have been only a few studies on identifying the subject. Most of the measurement instruments relate to safety climate rather than safety culture.

Reason (1997, pp.191) proposes that a safe culture is an “informed culture”. An informed culture is “one in which those who manage and operate the system have current knowledge about the human, technical, organizational, and environmental factors that determine the safety of the system as a whole” (Reason, p.294) Reason argues that an informed culture has four different ingredients : (1) reporting culture, (2) just culture, (3) flexible culture, and (4) learning culture. A reporting structure refers to an atmosphere of trust in which people are willing to “confess” to their errors. In other words, a reporting culture is a supporting culture of people who report. Also, an informed culture is a just culture, with an atmosphere in which people are clear about what act is acceptable, and what is not. Reason believes that if the line between safe and unsafe behavior is clear, then unacceptable acts can be reported without any fear. Thus, a reporting culture can not be successful without a just culture. A flexible culture is the one that can adjust to changing internal and external demands. Wieck and Sutcliffe (2001) relate the concept of flexible culture with the characteristics of HROs, which “allow decisions to migrate to expertise during periods of high-tempo activity”. They argue that if hierarchies are more flattered, the information can flow more freely, and a flexible culture is more possible. The last dimension of culture offered by Reason is a learning culture. A reporting, just, and flexible culture help people understand the best practices and learn from past mistakes.

Some studies have attempted to develop assessment instruments for safety culture. For instance, Gibbons et al. (2005) developed their instrument for maintenance of airlines with the following factors: (1) Organizational Commitment (safety value, work environment, safety fundamentals, and safety training), (2) Supervisors (supervisory environment, maintaining standard), (3) Informal Safety System (accountability, technician's authority, professionalism), and (4) Formal Safety System (Reporting system, Response & feedback, and Safety Personnel). Following are few statements that point to meaning of some of their factors:

- Safety Value: "management is more concerned with making money than being safe (true or false)"
- Safety Fundamentals: "shift work and day-off scheduling policies at my company greatly contribute to stress and fatigue in technicians (true or false)"
- Work Environment: "My company ensures that the environment (e.g. lighting, air conditioning, ventilation) is conductive to effective maintenance work (true or false) "
- Supervisory Involvement: "Supervisors distribute the workload evenly among technicians (true or false) "
- Accountability: "Management shows favoritism to certain technicians (true or false)"
- Reporting System: "Technicians don't bother reporting mishaps or close calls since these events don't cause any real damage (true or false)"

Based on our proposed definition of safety culture and safety climate, we believe that some of their measures are actually tapping safety climate, rather than safety culture.

A more comprehensive organizational safety culture survey can be developed by adapting multiple methods, as suggested by Ostrof et al. (2003) for organizational culture. These include: Organizational Culture Inventory (OCI) and Competing Values Framework (CVF), as well as Organizational Culture Profile (OCP), in order to assess multiple levels of organizational safety culture. OCI is a survey with 120 items that assess 12 sets of normative beliefs that are categorized in three types of organizational cultures: constructive culture, passive-defensive culture, and aggressive-defensive. We refer the reader to Cooke & Szumal (2000) for more detail explanation of OCI. Another instrument, named CVF (Quinn & McGrath, 1985; Quinn & Rohrbaugh, 1983), measures the values and norms, and classifies culture into four types namely a group culture, developmental culture, hierarchical culture, and the rational culture. The OCP was developed to measure person fit (O'Reilly et al., 1991). It has 54 items for values and uses the Q-sort methodology to categorize the organization from least characteristic to most characteristic.

Future research is needed to implement these instruments for assessment of safety culture and its different types. As an example, Ron Westrum (1992) has proposed a classification of safety culture types including generative, pathological, and bureaucratic. Generative organization refers to the one with deep learning characteristics. Such organizations encourage people to observe, make conclusions, and report to higher managements. Pathological organizations do not support new ideas, punish the failures, and in Reason and Hobbs (2003, p.156) views, "keep one step ahead of the regulator". The third type, which is bureaucratic, is a culture between the fist and the second one. These types of organizations mostly focus on fixing the proximate/superficial causes of safety problems, rather than more fundamental root and causes.

As another example, Hudson (2002) extends these three types of safety culture to five types including Pathological ("who cares as long as we don't get caught") , Reactive ("safety is important; we do a lot every time we have an accident"), Calculative ("we have systems in place to manage all hazards", Proactive ("we work hard on the problems we still find"), and Generative ("we know that achieving safety is difficult; we keep brainstorming new ways in which the system can fail and have contingencies in place to deal with them"). Hudson believes that organizations need to pass each stage (type) in order to achieve the next stage.

5.9.2 Safety Climate

5.9.2.1 Definition

In order to define the concept of safety climate, we first clarify the concept of climate and then specify safety climate as a subset of organizational climate. Climate is widely considered to be a multi-dimensional phenomenon describing the perception of formal and informal organizational policies, procedures, and practices (Reichers & Schneider, 1990). However, there are a number of issues that originally caused confusion and contradictions about this term.

One reason is the overlap of this term with safety culture. Some of the more recent work (e.g. Denison, 1996) brought up the issue of similarity between culture and climate. Denison argued that both culture and climate refer to a common psychological phenomenon within an organization. Ostroff et al. (2003) believe that the cause of this conceptual overlap is not related to the theoretical treatment, but is due to the empirical methods to assess these concepts. A number of quantitative culture studies appeared during the 1990s that have used a survey style very similar to climate studies, and often with the same dimensions. Also, some of the culture studies focused on the assessment of perceptions of organizational practices. It can be argued that these studies mostly consider the artifact layer of culture rather than its deeper layers. According to Zohar (2003), the use of safety culture and climate "…interchangeably, or operationalising culture with climate scales, as in the common practices, results in conceptual slippage damaging both." (p. 123)

The three other causes of disagreements about climate came from the objective versus perceptual nature of climate, the level of analysis, and the aggregation of climate perceptions. (Ostroff et al., 2003) Today, it is widely accepted that climate is a perceptual construct originated at the level of the individual, named psychological climate. If the consensus among the individuals' perceptions is exited, their perceptions can be aggregated to create subunit or organizational climate. (James, 1982) However, there are still some contradictions about the aggregation problem in climate.

Schneider (1975) proposed that climate research should move from a molar perspective toward climate for a specific outcome and goal such as climate for service. This notion created a ground for constructing the term safety climate (Zohar, 1980), which is a climate for safety. From then, several definitions have been proposed in different industries. For instance, Zohar (2003) defined the term as "….shared perceptions with regard to safety policies, procedures, and practices." (p.125). Mearns et al.(2003), in offshore industry, also expressed the term through attitudes. Cheyne et al. (1998) highlighted safety climate as a temporary state measure of safety culture. Wiegmann et al. (2002) based on the commonalities found in the literature in the definitions of safety climate, concluded that "safety climate is the temporal state measure of safety culture, subject to commonalities among individual perceptions of the organization. It is therefore situationally based, refers to the perceived state of safety at a particular place at a particular time, is relatively unstable, and subject to change depending on the features of the current environment or prevailing conditions" (p.10).

We proposed the following definition of safety climate based on the concept of organizational climate, referring to the model represented in the Figure (5.4):

> Safety climate is a perceptual construct originated at the level of individual, named psychological safety climate. Psychological safety climate is the individual perception about organizational safety structure and practices. If the consensus among the individuals' perceptions is exited, their perceptions can be meaningfully aggregated to represent subunit or organizational safety climate.

5.9.2.2 The Elements of Safety Climate

Today, climate researchers have mostly focus on the multi-dimensional climate rather than a global nature. They have proposed some dimensions such as reward, conflict, support, risk, and many more. (Ostroff et al., 2003)

Similarly, the concept of safety climate has been described multi-dimensionally. Flin and his colleague (1998 & 2000) reviewed 18 studies and characterized five main dimensions of safety climate including management/supervision, safety systems, risk, work pressure and competence. Cheyne et al. (1998) also found other dimensions such as “communication”, “individual safety responsibility”, and “group involvement in safety” as important ones. Zohar (1980), too, has a five-dimensional construct for safety climate including “perceived management attitudes towards safety”, “perceived effects of safe conduct on promotion”, “perceived effects of safe conduct on social status”, “perceived organizational status of safety officer”, “perceived importance and effectiveness of safety training”, “perceived risk level at work place”, and “perceived effectiveness of enforcement versus guidance in promoting safety” (p. 98). Comparing Zohar’s dimensions with the previous mentioned items, it can be concluded that three terms, i. e. “incentives for safety”, “involvement on the possibility for promotion”, and “social status” are important to be considered as well.

A number of surveys have been developed by researchers assessing the various dimensions of safety climate. The main focus of these studies is to build the measurements in a way that can predict safety performance effectively. Trying to achieve this objective, sometimes the items that are not part of the concept of climate are included. For example, the perception of employees about the adequacy of tools and equipment is not a real climate aspect, but since it has an effect on the safety output of organization, including this item can make safety climate a better predictor. Our proposed risk model (Section 5.12) reflects the opinion that safety climate affects individuals' motivations and finally individuals' safety performances. But the total safety performance of organization is not only related to individuals' performances, but also depends on the physical system that individuals work with. We propose that safety climate measurements should only be devoted to the items that have really climate nature and have an effect on individuals' motivation. Using this kind of safety climate concept in a comprehensive model of accident renders a more effective safety prediction.

5.9.2.3 The Antecedents of Safety Climate

Most of climate researchers have focused on the outcomes of climate rather than its antecedents. Ostroff et. al (2003) As we mentioned in the previous section, safety climate emerges from individuals' perceptions about organizational safety structure and practices, and thus the most important antecedent of safety climate would be organizational safety structure and practices. There is some evidence on the relation between climate and the organizational practices and structure. For example, Kozlowski & Hults (1987) have shown a relation between technical, structural, and reward systems and a climate for technical updating. Besides, Klein & Sorra (1996) and Schneider (1990) strongly believe that human resource management practices are the causal root for the creation of specific types of climate, but there have been limited studies on testing the presence of these linkages. (Kopelman et al., 1990)

Another point that is highlighted in the definition of safety climate is the concept of "consensus". Ostroff et al. proposed that "…these shared perceptions will develop only when strong emergent processes are enacted in organization" (p.567).

Thus, “emergent process factors” including supervision/leadership, social interactions, and homogeneity are the other antecedents of climate. Although emergent process factors are affected by organizational practices, because of the importance of these processes as antecedents of climate, we considered them as separate factors influencing climate.

One of the emergent process factors, homogeneity, is based on the Attraction-Selection-Attrition (ASA) theory developed by Schneider (1987).The idea is that individuals are attracted to organizations that have attributes similar to their own characteristics and views. The selection and hiring procedures in a given organization try to choose people who have more similarity to the organizational attributes. Individuals would leave the organization if their attributes don’t fit the characteristics of the work context. As a result the organization will end up with more similar people who perceive the work context more similarly. With this explanation, it is clear that the quality of selection in organizational practices influences homogeneity. (see Figure 5.7)

Another factor in emergent process, i.e. social interaction, is based on the process of interaction and social exchange in the development of a specific interpretation of the work context among the members of the same group. Ostroff et al. (2003) believe that informal interaction groups have more effects on the formation of a shared climate than formal interaction groups. With this description of social interaction process, we can propose a relation between “team systems”, a human resource function of organization, and the social interaction factor. (see Figure 5.7)

In the emergent process, a third major factor is "leadership". Kozlowski & Doherty (1989) believe that leaders or supervisors act as interpretive filters for all group members' perceptions about the relevant organizational structure and practices. For example, Borucki & Burke (1999) have shown a relation between the importance of service to managers and the employees' perceptions of the service climate. Rentsch (1990) highlights the fact that those leaders that clearly communicate their own interpretations with organizational members are more likely to create a common interpretation among them. Kozlowski & Doherty (1989), for example, have tested the strong interaction between leader-member relationship and within-unit consensus on climate perception. This concept can lead to different climates in different groups of organizations. For example, according to Zohar & Luria (2005) , a supervisor who encourages workers to ignore some safety procedures for the sake of production creates the potential for different safety climates within an organization. It can be argued that supervisors' behaviors, like any other individuals in an organization, are in turn affected by organizational practices (human resource practices). (see Figure 5.7))

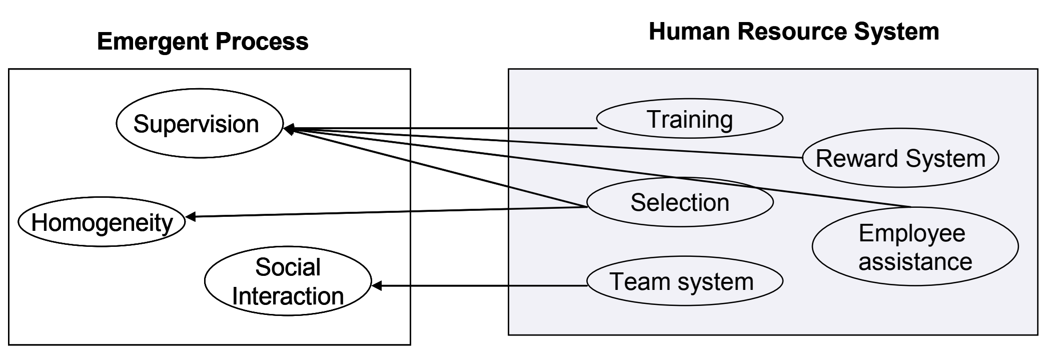

Figure 5.7 The link between "emergent process" & "Human Resource System"

5.9.2.4 The Outcomes of Safety Climate

The outcomes of climate have been studied at the individual-level and unit /organization-level. (Ostroff et. al 2003)

At the unit/organization level, for example, Lin, Madu, & Kuei, (1999) have linked the global climate dimensions to the quality management outcomes. Climate for service has been related to employee perception of service performance, and in turn to organizational financial performance (e.g. Borucki & Burke, 1999). Also, Zohar (2000) has shown the relation between group-level safety climate and objectively measured injuries. The relations of unit-level safety climate have been shown in Figure (5.3) as the links between organizational safety climate and organizational performance, and also group-level safety climate and group performance.

At the individual-level, some studies have been devoted to the effects of psychological climate on individual-level outcomes. For example, Johnson & McIntyre (1998) have shown the relation between global dimensions of psychological climate and satisfaction, and Pritchard & Karasick (1973) have related psychological climate and performance. Some other individual-level researchers have focused on the relations between unit-level climate and individual-level outcome. For example, unit-level climate has been related to individual safety behavior (Zohar, 2000), satisfaction, turnover intention, absenteeism, and involvement (e.g. Jackofsky & Slocum, 1988).

The effect of unit-level safety climate on individual performances has been shown in the Figure (5.4) through the cross-level path of influence. Section (5.10) describes the path of influence of climate on individual performances in more detail.

5.9.3 Organizational Safety Structure & Practices as a Link between Safety Culture and Safety Climate

5.9.3.1 Definition

In the framework represented in Figure (5.1), organizational practices, management practices, policies, and procedures, are covered under the title of organizational practices. Ostoff et al. (2003) define organizational practices as "the linking mechanism between culture and climate, not a measure of either culture or climate". In other words, culture is not equivalent to practices, but it leads to a set of practices. On the other hand, practices are the antecedent of climate as well. But, climate is the organizational members' perceptions of the practices, not the objective practices. (Rentsch, 1990) For example, a culture that values the customer may lead to adaptation of a set of reward practices about how to treat customers. Then, a service-based climate can be created based on organizational members' perceptions about these practices and the agreement among them. (Schneider, 1990) "If the adapted practices do not reflect the culture, or if practices are poorly implemented, climate perceptions may develop that are counter to the underlying cultural values and assumptions" (Ostroff et al., 2003, p. 576).

In the model represented in Figure (5.3), organizational safety practices are the organizational practices that have effects on Safety Critical Tasks (SCTs), introduced in Section (5.7). For example, since maintenance performance is a safety critical task, all organizational practices such as human resources, calibration and testing and so forth are assumed as organizational safety practices. The same argument applies to safety structure. Although organizational structure and organizational practices have overlaps and are strongly interrelated, in this report we most cover organizational practices, while a deeper study of the effects of organizational structure on safety needs future effort.

5.9.3.2 The Content of Organizational Safety Structure

For structural factors, we refer to the set of "design factor" in Mintzberg's theory (1983). Several researchers have developed questionnaires to measure the organizational structure. As an example, we name the one developed by Doty et al. (1993) Their factors include the Mintzberg's set of design factors including the key coordination mechanism, the key parts of the organization, the type and degree of centralization, formalization, specialization and hierarchy. The following are their sample questions for different factors:

- Vertical and Selective decentralization:

  "To what extent do you **delegate** decision making authority in each of the following areas…

  • Hiring mid-level management personnel?

  • Making major changes in the way your organization produces its products and/or service?"

- Coordination Mechanism

  "To what extent does your organization **coordinate activities** through…

  (Direct Supervision)

  (Standardization of Work)

  (Standardization of Skills)

  (Standardization of Outputs)"

- Formalization

  "To what extent is your organization currently characterized by …

  • Strict enforcement of written rules"

- Hierarchy of Authority

"How many organizational levels are there below you (do not include yourself)?"

- Specialization

  "How strongly do you agree or disagree with each of the following statements about your organization?

  • Most employees do similar types of work."

- Key Part of the Organization

  "Approximately what percentages of your organization's employees are in …

  a. Line operations, performing the basic work related directly to the production of products or services?

  b. Line management positions below upper management and including first line supervisors?"

5.9.3.3 The Content of Organizational Safety Practices

Organizational safety practices include all organizational practices/activities that support the resources, tools/equipments, and human actions in the unit process model (see Figure 5.6) that ultimately link to the safety critical tasks. We classified organizational safety practices into four groups including (1) *resources-related* activities, (2) *procedure-related* activities, (3) *human-related* activities, and (4) *common* activities. All the first three of activities are supported by the fourth one (common practices). Common activities include *design*, *implementation*, *internal auditing,* and *internal change system*. (see Figure 5.8)

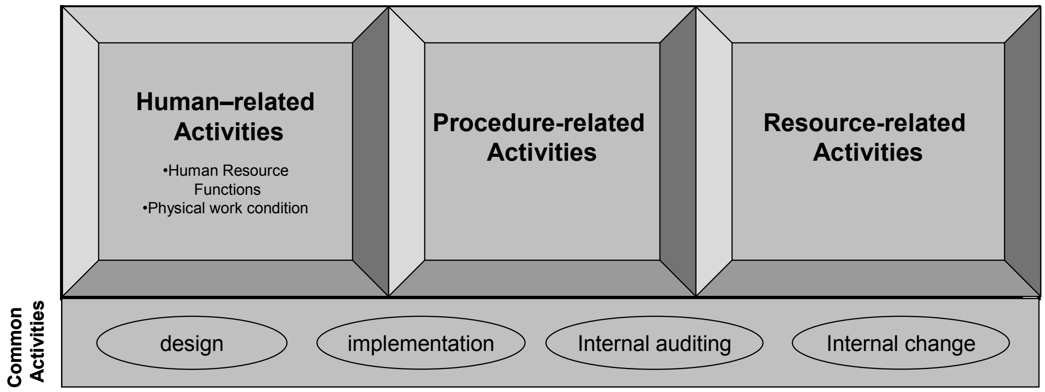

Figure 5.8 Organizational safety practices

Resource-related and procedure-related activities are the practices that support resources and procedures of the unit process model, respectively. They are more specific than human–related activities. They depend on the specific unit process that supports the related SCT .For example, in the case of maintenance unit process, one of the resources-related activities is in-house calibration and test that supports locally produced tools and equipments, and one of the procedure-related activities is alteration that supports records and reporting. Chapter 6 provides a more detailed example for maintenance unit process and its related organizational safety practices.

Human-related activities are those that support individual performances in the unit process model as well as in all other organizational practices (e.g., Resource-related activities). Human-related activities include the human resource functions and also the quality of physical work conditions that affect human actions. The physical work conditions such as lighting, ventilation, and human-system interface are mentioned in all human reliability models (e.g. IDAC; Chang & Mosleh, 2004b) as influencing factors on human error.

Human resource functions are extracted from a study by Ostroff (1995) that considers the functions that human resource system should cover. Since in our framework by "organizational practices", we mean the "actual" organizational practices of organization, we should consider all functions that an appropriate human resource system should do (not the ways it currently does). Ostroff in her study identified all human resource activities, and using a survey she assessed the importance of each activity in different industries and different business strategies. Table (5.1) shows all human-related activities. The description of all human resource functions can be found in the Appendix A.

Table 5.1 Human-related activities

Human-related Activities	
Physical Work Conditions	**Human Resource practices**
•Lighting •Ventilation •Human-system interface •etc.	•Selectivity in recruiting/ Hiring •Internal staffing •Contingent Workforce •Training and Employee Development •Appraisal •Compensation and Reward Systems •Job Analysis •Job Enrichment •Team systems •Employee Assistance •Due process •Employee Voice/ Empowerment •Diversity •Legal Compliance •Safety •Union Relation

The next layer of organizational safety practices, named common activities, include “design”, “implementation”, “internal auditing”, and “internal change system”. (see Figure 5.8) All bottom layer “procedures” and “resources” in the framework (the procedures and resources that do not have any lower layer supporting factor) are affected by design, implementation, internally auditing, and internal change factors.

Design is planning an item (procedure or resource) so that is in accordance with organizational policies and satisfies the characteristics of a qualified item. *Implement* is to execute what has been designed for the item. *Internal auditing* refers to monitoring the item against the policies and objectives characteristics, and also reporting the findings. *Internal change* translates into taking action to fix the findings problems in the item. Internal auditing and internal change system are part of *organizational learning* process, and more specifically *single-loop learning* (Agyris & Schon, 1996, Carroll et al., 2002). In single-loop learning the actions are modified based on the gap between the real and expected results.

These four activities (design, implementation, internal auditing and change) refer to the PDCA cycle (plan, do, check, and act) that has its roots in the quality control field (e.g. Shewart, 1939 and Deming, 1986) and the current ISO 9001-2000.

5.10 Individual Safety Performance and Its Antecedents

It is important to consider the effect of underlying cognitive, emotional, and physical factors when evaluating human safety performance. Llory (1992) maintains that such human factors are at the root of most safety problems. We refer the reader to Chang and Mosleh (2004) for a description of the IDAC model for human reliability analysis for use in the nuclear power industry, where these factors and their significance have been discussed. Based on the IDAC model, an operator interacts with the external world (i.e. other operators, the system, the external resources) to achieve the operator's goals. The operator's problem-solving process is influenced by the factors, internal and external to the operator. The internal influencing factors relate to the operator's psychological, cognitive, and physical states. The external influencing factors include team-related factors, organizational factors, and those, usually beyond organizational control. The team related factors relate to the team structure, team tasking, and interactions between teammates. The organizational factors relate to influences resulted from organizational emphases (e.g.,productivity vs. safety), and organizational practices (e.g. financial and human resources management and task planning). Examples of factors usually beyond organizational control are the conditioning events (i.e. latent system faults) and environmental factors (e.g. change of habitation due to unanticipated events). The external factors must be perceived by the operator to influence the operator. Realization of the states of the external factors could affect the internal factors. The internal and external influencing factors are collectively labeled as Performance Shaping Factors (PSFs). Figure (5.9) is a modification of the IDAC internal PSF categories. We added "psychological climate" to the model, which addresses individual perceptions of organizational safety practices.

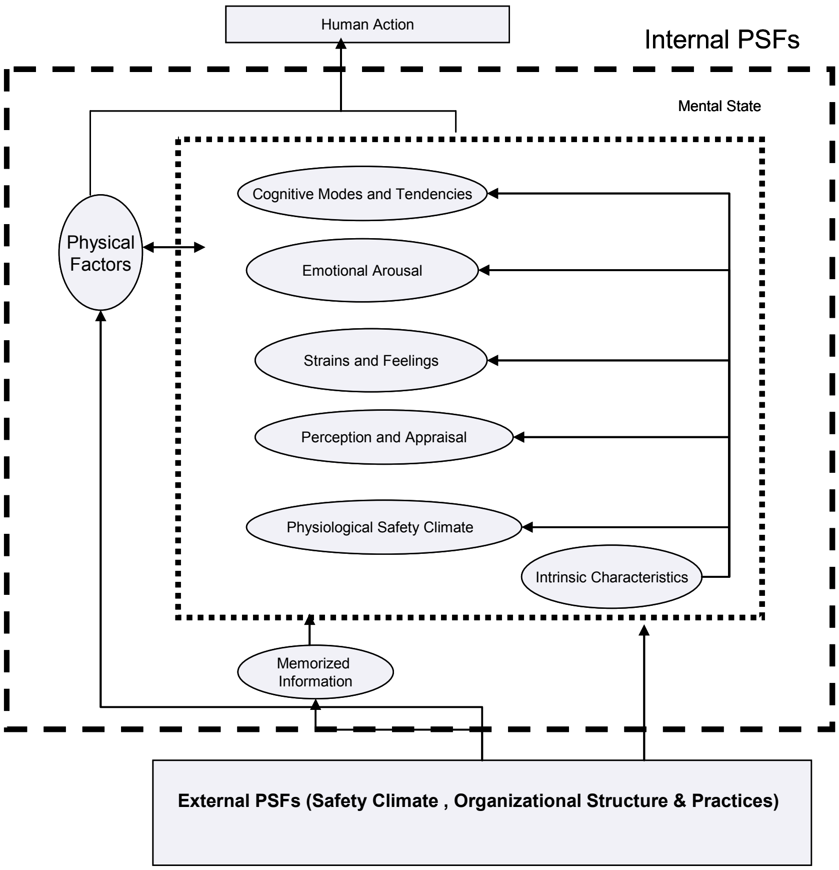

Figure 5.9 Internal PSF categories adapted from IDAC (2006)

Our concern in this report is mostly organizational factors and their paths of influence on human performance; therefore a simplified version of individual-level performance shaping factors is utilized. Boxall and Purcell (2003) proposed that performance is a function of ability (A), motivation (M), and opportunity (O). We use the AMO theory to separate the attitude node (in Figures 5.1 to 5.4) into these three general components. In most human reliability literature such as IDAC, ability (physical competence as well as knowledge) and motivation are referred to internal performance shaping factors (PSFs). The definition of opportunity is very vague in the AMO-framework, but we define opportunity as some temporal opportunity (or lack of it) such as time opportunity (e.g. time pressure due to work schedule) or physical opportunity (due to physical working environment such as lighting).

Motivation is most affected by psychological climate, referred to in such literature as Kopelman et al. (1990) and Parker et al. (2003). As Figure (5.3) describes, psychological safety climate, that is individuals' perceptions of safety practices, is influenced by group safety climate and personal value. The individuals' values are affected by their background and the organizational selection process.

Ability and opportunity are the factors that can be most affected by organizational practices and structure. For example, the quality of training and selection in an organization affects the level of knowledge, and the quality of time schedule as well as staffing affects time opportunity. The link between organizational practices and A and O can also be supported by Kopelman et al. (1990). In their analysis of organizational productivity, human resource affects motivation through climate. The productivity /performance is not only affected by motivation but also is a function of other factors that are directly affected by human resource practices.

Although some of the literature such as Neal and Griffin (2002) make a connection between knowledge and climate, it can be argued that while this connection shows a correlation between climate and knowledge, this doesn't mean that climate is the antecedent of the level of knowledge. It can be argued that climate and the level of knowledge are correlated, because the quality of training (that is antecedent of the level of knowledge) impacts employees' perception and the climate.

Figure (5.10) shows the relation between individual PSFs and the individual performance. Deviation of human performance from standard safe action can be in two forms of error and/or violation. Error is the unintentional deviation, whereas in contrast, violation is an intended action that has taken place in breach of a set of rules.

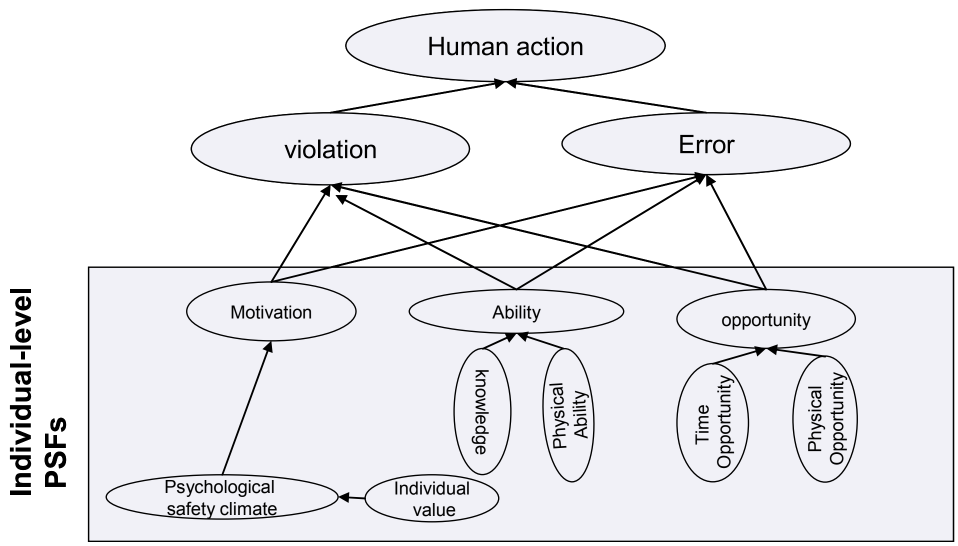

Figure 5.10 The links between "Individual-level PSFs" and "Human Action"

5.11 Contextual Factors

As Figures (5.1 to 5.4) show, the organizational culture is affected by industry and business environment, national culture, and the organization's vision, goals, and strategy (Aycan, Kanungo, & Sinha, 1999). The elements of "industrial and business environment" are adapted from contextual factors of Mintzberg's theory (1983), and are listed in Section (5.11.1). Also, as another contextual factor, we point out to regulation in Section (5.11.2). Although some aspects of regulatory environment have overlap with the items listed in Section (5.11.1), because of their importance to safety, we have discussed them separately discuss about it. The last contextual factors are in the category of physical environmental such as climatic conditions. (Section 5.11.3)

5.11.1 Industrial and Business Environment

Doty et al. (1993) applied Mintzberg's theory and developed a questionnaire to measure contextual factors. Here, we list a few example questions from Doty's questionnaire:

- Environmental Turbulence
  "Over the past year, how many important **changes** have occurred in the behavior of key…
  - Suppliers?
  - Competitors?
  - Customers/clients?
  - Regulators?"

a) Environmental Complexity
"To what extent does <u>your</u> organization…
- Face a complex external environment?"

b) Analyzability and Number of Exceptions
"To what extent…
(Analyzability)
- Is there a clearly known way to do the major types of work that these groups deal with?"

(Number of Exceptions)
- Do these groups perform about the same tasks in the same way most of the time?"

5.11.2 The Effects of Regulatory Environment

The effects of regulatory environment are either through policies and standards, or through the quality of a given regulatory auditing system. The effects of regulatory environment through policies, to some degree, are related to the environmental turbulence and the number of exceptions herein, as discussed in the previous section. Understanding the impacts of regulatory policy making needs future efforts. In this thesis, we mainly refer to the regulatory auditing responsibility. Regulatory auditing is a three stage task and consists of:

a) assessing whether the safety policies are in compliance with regulations, and whether organizational practices are designed according to safety policy;
b) assessing whether organizational performance practices are implemented based on designed statements;
c) reporting the detected deficiencies in a timely and effective manner.

Most of the procedures and resources (such as manuals, inspection procedures, calibration and test procedures, and tools/equipments) in the organization are audited by regulation directly and therefore there should be some links between regulatory auditing system and "organizational safety practices" in the organizational safety framework. In other words, the actual quality of org. safety practices and their related procedures and resources are affected by the quality of the regulatory auditing system as well.

Figure (5.11) pictures the relationships within the actual state of organizational practices and the effects of the regulatory auditing system. This relationship has been explained through a three dimensional graph.

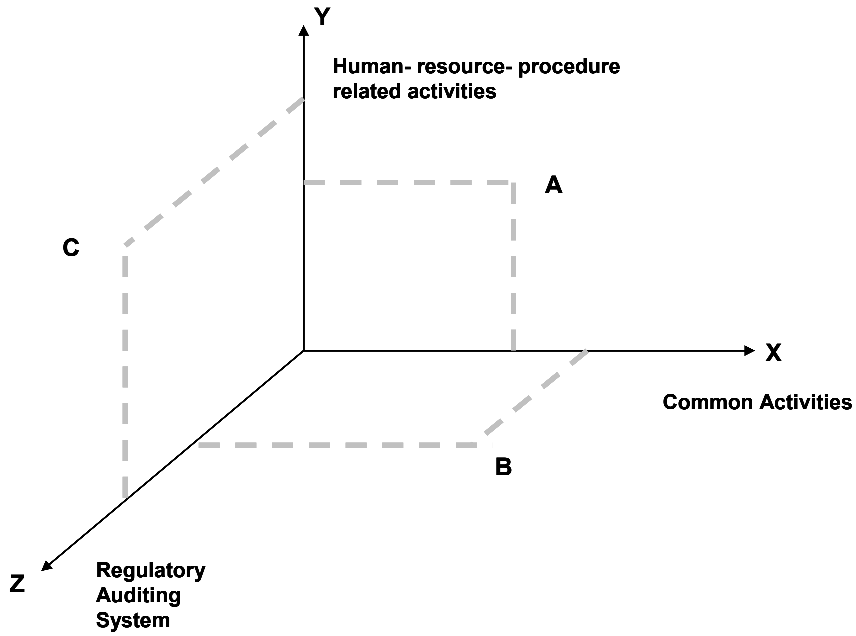

Figure 5.11 The relation between organizational safety practices and the Regulatory Auditing System

The axes of the graph are:

- X-axis: "Common" activities, which refer to implementation, design, internal auditing and change system (see Section 5.9.3.3)
- Y-axis:"Human-related"/"Resource-related"/"Procedure-related" (HRP)activities
- Z-axis: Regulatory Auditing System

Each point in the plane XY represents the state of common activities with respect to each HRP activity. For example, point (A) shows how good the specific HRP activity is designed, implemented, audited and changed internally. Each point in the plane YZ represents the state of RAS regarding HRP. For example, point (B) shows how good the specific HRP practice is audited externally by the regulatory system. Each point in the plane YZ represents the state of RAS regarding the internal auditing and change system. For example, point (C) shows how good the internal auditing and change system is audited externally by the regulatory system. Based on this three dimensional relation, the actual state of each HRP activity can be shown as a function of A, B, and C. (see Figure 5.12)

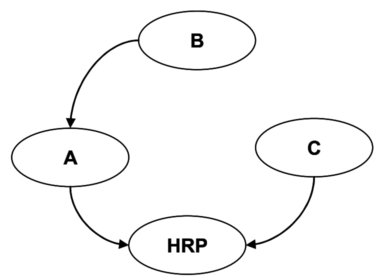

Figure 5.12 The actual state of HRP activities as a function of common activities & the regulatory auditing system

5.11.3 The Effects of Harsh Physical Environment (Climatic Conditions)

Harsh environmental factors such as weather conditions have also direct effects on the system safety through hardware hazards and the adverse conditions for individuals who operate the system. The path of influence of weather condition in safety framework is described in Chapter 6 through the example application.

5.12 Schematic Representation of the New Theory: From Organizational Factors to Accident Risk Scenarios

This part depicts the cross-level path of analysis highlighted in Figure (5.4), summarizing all detail relations described in Sections 5.1 to 5.11. The condensed causal framework is represented in Figures (5.13) and (5.14). Both figures show the same paths of influences, but Figure (5.13) is more detailed in technical elements.

The development of an organizational safety causal model starts from the *system risk model* (the scenarios on the top of Figure (5.13)) and moves to the organizational root causes (the bottom layers of Figure (5.13)). A top-down risk model delineates the possible risk or hazard scenarios (ESDs) and decomposes them into their contributing elements. The events, conditions, and causes of the scenarios are incorporated through the FTs. The top events of fault tress (e.g. System 1) are plugged into the ESDs. ESDs represent a set of possible risk scenarios where, given the occurrence of the initiating event, the state of System 1 (a Pivotal Event) determines whether the sequence leads to success (end state S), when it works, or a human action is required, when it fails. Given the success of human action, the final outcome would be success state (S). The failure of Human Action leads to failed state F. The failure of System 1 can be due to different types of causalities. One source of system failure can be related to organizational activity that is the concern of this causal framework. The other sources of failure can be related to an inherent hardware failure that represents failure mechanisms which are beyond the control of the organization in charge of operating and maintaining the technical system (e.g., related to the manufacturer).

The group or individual performances that have direct effects on the elements of technical system risk scenarios are named *Safety Critical Tasks (SCTs)*. For example, maintenance is a safety critical task, since it directly affects hardware failure (an element of risk scenarios). In general, SCTs can be either events explicitly specified (e.g. human actions) in the accident scenarios, or implicitly through model parameters (e.g. equipment failure rate). SCTs help to focus what matters most for safety among many activities in the organization.

The *Unit process model* (e.g. maintenance unit, operation units) includes the "direct" activities that affect SCT (which is the unit output). The direct activities are decomposed to their direct resource, human factor, and procedures in the unit process model. The rest of the causal model will describe how the organizational factors affect the SCTs through their effects on the direct resources, procedures and individuals' performances in the unit process model. In the scope of this project, organizational safety factors are the social (culture and climate) and structural (organizational texture and managerial practices) aspects of an organization that influence safety critical tasks.

Organizational safety practices include all organizational practices/activities that support the resources, tools/equipments, and human actions in the unit process model (see Figure 5.6) that ultimately link to the safety critical tasks. We classified organizational safety practices into four groups including (1) *resources-related* activities, (2) *procedure-related* activities, (3) *human-related* activities, and (4) *common* activities. All the first three of activities are supported by the fourth one (common practices). Common activities include *design*, *implementation*, *internal auditing,* and *internal change system.* Internal auditing and internal change system are part of *organizational learning* process, and more specifically *single-loop learning* (Agyris & Schon, 1996, Carroll et al., 2002). In single-loop learning the actions are modified based on the gap between the real and expected results. The four common activities (design, implementation, internal auditing and change) refer to the PDCA cycle (plan, do, check, and act) that has its roots in the quality control field.

Organizational safety practices affect resources and procedures in the unit process model, through the direct link indicated in Figures (5.13) and (5.14). Organizational Safety Structure & Practices also affect *internal PSFs* and ultimately individual safety performance through two different paths of influence: (1) Organizational safety practices collectively influence *organizational safety climate*, which is the shared perception of employees about actual organizational safety practices. Organizational safety climate affects *group safety climate*, which in turn influences *psychological safety climate* (an element of individual-level PSF). Psychological safety climate is the perception of organizational safety practices at the individual level. It impacts individuals' motivation in the unit process model. For example, high quality training programs and work conditions collectively create a climate in which employees believe in their managers' commitment to safety. This belief impacts the employees' motivation. This is the indirect effect of organizational safety practices on individual-level PSFs, and (2) Different sub-factors in Org. Safety Structure & Practices can also directly impact individual internal PSFs. The direct effects are caused by the influence of "human-related activities" on the "ability" and "opportunity". For example, a low quality work environment, such as poor air conditioning and lights, can affect physical opportunity, and training has effects on people's knowledge.

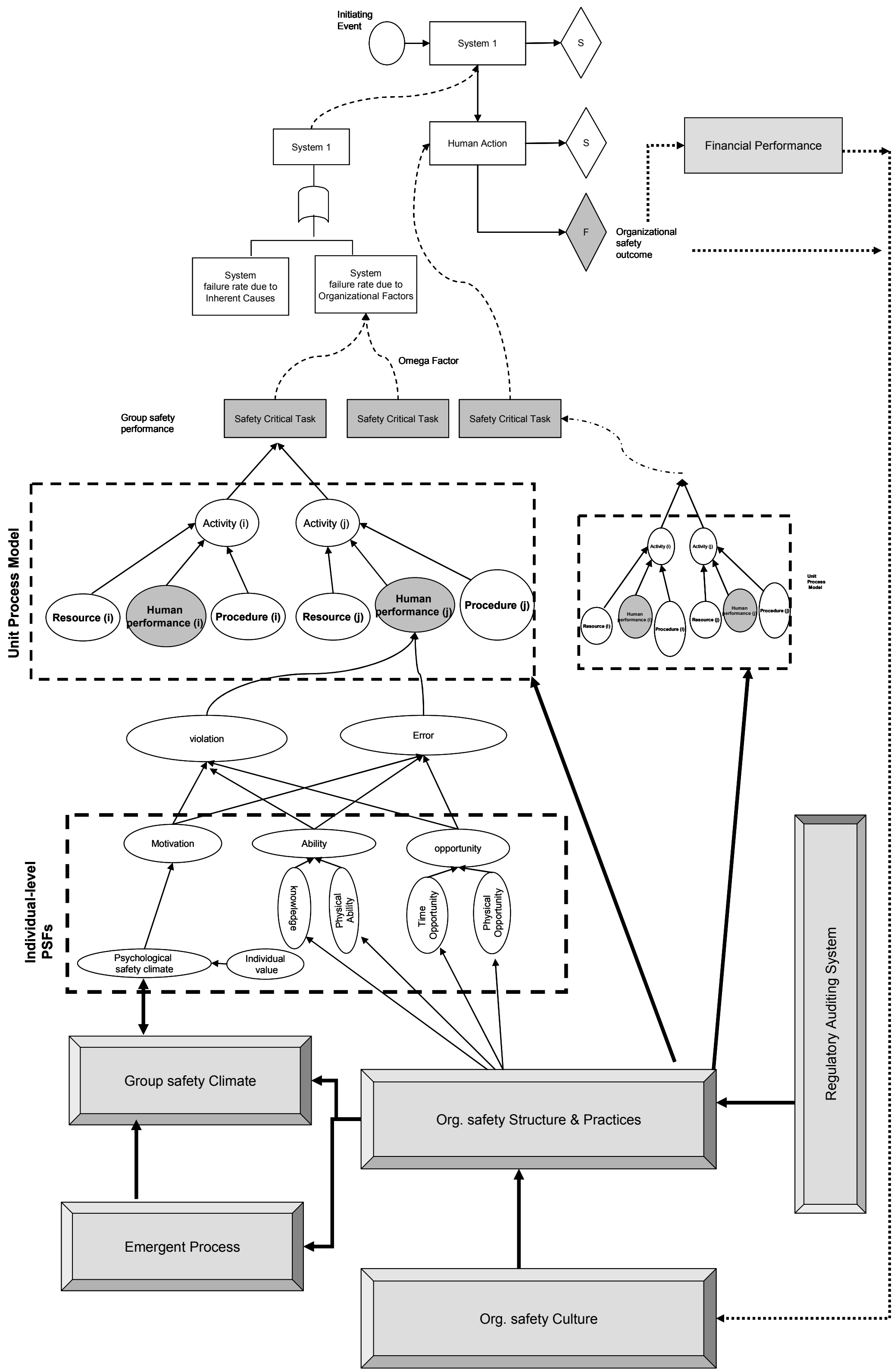

Figure 5.13 Schematic representation of SoTeRiA (#1)

The strength of the shared climate depends on the *emergent process* including the social interaction process, leadership/supervision, and homogeneity in the organization. As Figures (5.13) and (5.14) depict, the emergent process is also affected by organizational practices.

It should be added that some of the individuals' opportunities, are not only directly affected by organizational practices, but also by supervisors' behavior. For example, the time pressure due to bad schedule not only is affected by human resource function (e.g. staffing), it is also related to supervisors' performances. This relation is not represented in Figures (5.13) and (5.14), in order to avoid complexity of the figures.

Some multi-level studies such as Zohar & Luria (2005) and Simard & Marchand (1995, 1997) have indicated that individuals' safety behaviors are strongly affected by their immediate supervisors, with organization providing the incremental effects. Thus, in Figure (5.13), we only include group safety climate, and not organizational safety climate, again in order to avoid the complexity of the figure.

Zohar & Luria (2005) discussed that some hazards in the organization (investigated by safety engineering) are only related to top management's procedural action (which support the direct link between organizational practices and the unit process model in Figures (5.13) and (5.14)), but workers' safety behaviors are affected by both procedural (which support the direct link between organizational practices and human individual-level PSFs in Figures (5.13) and (5.14)) and supervisory situations (which support the path from emergent process to group climate and ultimately to individual PSFs in Figures (5.13) and (5.14)).

At the organizational level, *safety culture* shapes managerial decisions regarding organizational safety practices and structural features. Culture is more stable and related to employees' ideologies, assumptions, and values. Climate is the perception of "what happens" in organization and can be described as temporary attributes of an organization. Culture defines "why these things happen" (Ostroff et al. 2003). As Figures (5.14) show, organizational culture is influenced by the type of industry and business environment, social/national culture, and organizational vision, goal and strategy. Besides, there are some feedback effects from organizational safety and financial performances on the safety culture. These effects are part of *organizational learning* processes, and more specifically *double-loop learning* (Agyris & Schon, 1996, Carroll et al., 2002). In the double-loop learning, the underlying assumptions, values, and policies that led to the specific performances are analyzed, questioned, and adapted (if it is needed).

There is a reciprocal relationship between the individual level and the organizational/unit level construct. Individual level constructs create the unit/organizational level construct, and individual level constructs are affected by the existing organizational level construct. For example, the individual psychological climate is affected by the organizational/unit climate. But these two mark different time phases, and the boundary assumption clarifies the direction of these effects.

Physical environmental factors (e.g. extreme weather conditions) also impact system safety through hardware hazards as well as the individuals who operate the system. *Regulations* have two different effects on safety: first, through policies and rules on organizational practices, and secondly through external auditing of organizational practices and unit process elements (such as maintenance procedures and resources).

The *financial performance* affects the safety performance both directly and indirectly. The indirect effects, for example, would be the feedback effects of financial stress on safety culture and ultimately on organizational practices such as training, work environment, operational procedures, etc. An example of the direct effects could be the collapse of morale because of certain news on extreme financial distress (e.g. possible bankruptcy). On the other hand, safety performance may affect the financial performance directly by increasing internal costs (e.g. higher insurance rates as a result of an accident) and indirectly through loss of goodwill, new regulations, and market value.

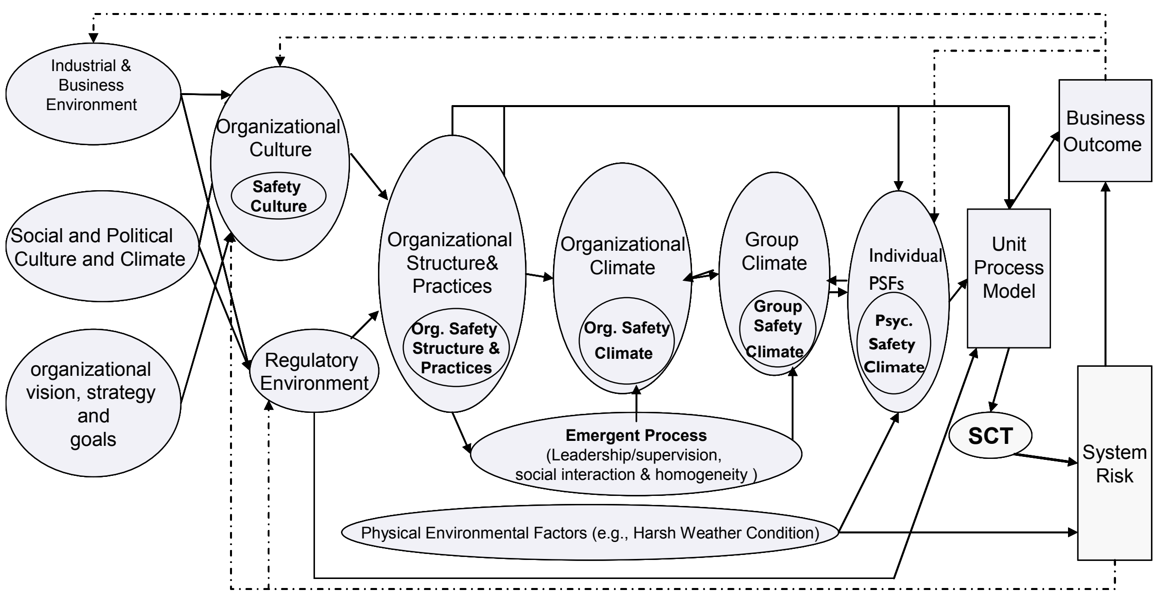

Figure 5.14 Schematic representation of SoTeRiA (#2)

6. APPLICATION TO AVIATION MAINTENANCE SYSTEM

6.1 Introduction

This chapter covers the last contributions of current thesis that are on the subject of implementation in aviation system. In the wake of several highly publicized aviation accidents in the past 15 years, safety is of primary interest to many travelers. There is an obvious push to reduce the number of accidents in any industry. Much of recent research in aviation, space exploration, and nuclear power operation has focused heavily on reducing risk through improvements in safety analysis.

In order to create the aviation-based safety causal model, we: (1) reviewed the literature in aviation safety analysis, (2) constructed our causal model based on the developed accident causation theory described in chapter 4, (3) and developed the sub-factors based on combination of general factors in organizational and safety literature, and the factors particularly specified in aviation literature.

NASA has addressed the effect of safety climate in flight operations in a review of the effectiveness of flight checklists (Degani and Wiener, 1990). Both erroneous use of checklists and non-compliance with rules mandating the use of checklists have contributed to many aviation incidents in the past 25 years. Among the influences that Degani and Wiener cite is airline culture, which they have defined to include supervision and management style, punitive actions, and physical location (that is, the differing social mores in different cultural groups). They also discuss the changing state of pilot duties and expectations imposed by changes in regulation at the federal level and the aircarier level; they maintain that shifting expectations strongly affect pilot morale and emotional state. Pilot actions are further influenced by outside factors including pressure to be on time, external distractions, and crew interaction dynamics.

Ten years after the Degani and Wiener study at NASA, Soeters and Boer (2000) discussed additional factors that influence pilot decision-making. They maintain that the "national culture" correlates with the number of aviation accidents and they offer multinational data for support. They indicate that the "mental programming" from the early years of education, which varies greatly across cultures, dictates how people relate to superiors and subordinates. In addition to affecting the pilots and mechanics' motivation and perceived level of authority, mental programming has an effect on regulatory oversight and company goals.

Spirkovsa and Lodha discuss a more specific aspect of the flight operations safety climate in their 2004 NASA report. The focus of their report is on pilot "situational awareness" as it is affected by interaction with ground authorities such as weather forecasters. Loss of situational awareness, especially in poor weather conditions, is a leading cause of Part 135 accidents and has been a contributing factor in Part 121 accidents. Additional demand on ground personnel during poor weather conditions leads directly to reporting difficulty and increased response time. These factors likely have a negative effect on the pilots' performance level as perceived task complexity, workload, and stress levels increase.

The research studies in the aviation field have highlighted some of the contributing factors to accidents, but there is no comprehensive study or model tracing the paths of influence starting from root organizational factors to the accidents and incidents. Aircraft accidents can be related to airline, airport, or air traffic control. All these are affected by contextual factors including regulatory factors, industrial and business environment, social and political culture and climate, and weather conditions. Some of the contextual factors such as weather condition affect the occurrence of accidents directly (not through the organizations) as seen in Figure (6.1). In this study we focus on the root causes that start from contextual factors and create accidents through the airlines. From the contextual factors, regulation (regulatory auditing system) and weather condition are considered in the model represented in this chapter. The effects of air traffic control and airport on the accident are also considered through accident scenarios, but the organizational factors rooted in airport and air traffic control have not been included in our causal model. In Section (6.2) of this chapter, the organization safety framework has been implemented for maintenance activities of a generic airline. Although the risk scenarios are general and cover both operation and maintenance, the effects of organizational factors are only modeled through the maintenance activities. Future study can be devoted to implementing the framework for operation (e.g., flight crew) as well. The gray parts of Figure (6.1) highlight the scope of implemented model in the Section (6.2).

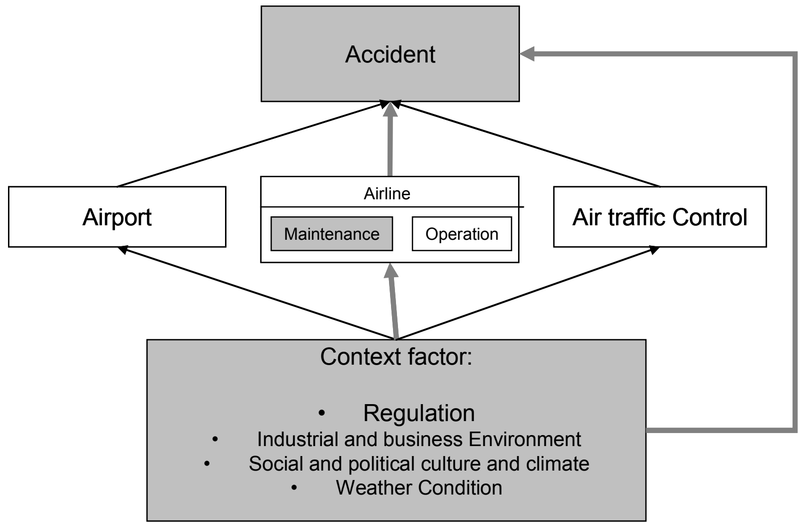

Figure 6.1 The scope of implemented model

In Section (6.3), we used the combination of system dynamics, BBN, ESD, and FT techniques to operationlize a simplified version of causal model described in Section (6.2). The objective of Section (6.3) is to demonstrate how a hybrid technique as proposed in the Chapter 4 can practically operate. System dynamics tool is added to IRIS[4] , which is a risk analysis software, in order to incorporate the dynamic causation mechanisms of the organizational framework. IRIS is built based on Hybrid Causal Logic (HCL) methodology (Wang, 2007). This part was collaboration with another student as part of which has been presented in Society for Risk Analysis Annual Meeting. (Mohaghegh et al., 2006)

[4] IRIS stands for Integrated Risk Information System developed by the Center for Risk and Reliability of the University of Maryland for the US Federal Aviation Administration.

6.2 Implementing SoTeRiA in Aviation Maintenance

Figure (6.2) shows the maintenance-related_paths of causality from airline to the system risk (aviation accidents involving aircraft operations). This model is constructed based on the proposed framework, SoTeRiA , represented in Chapter 5.

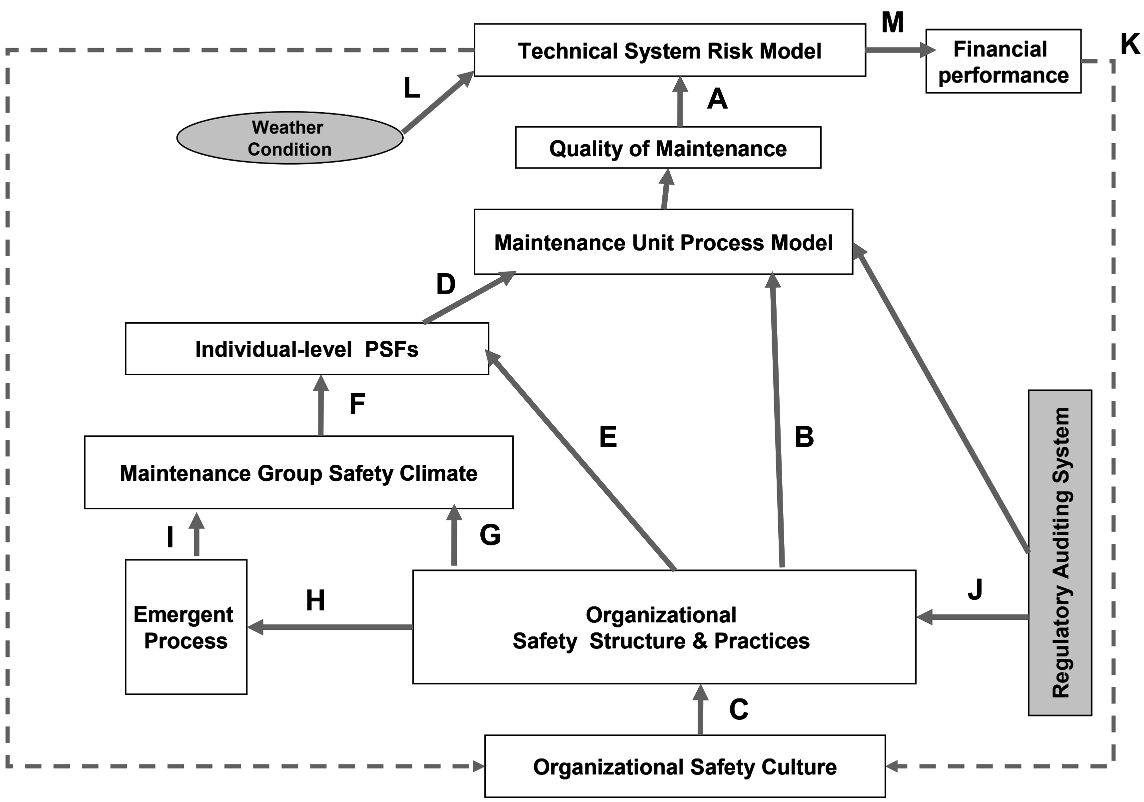

Figure 6.2 Safety framework (airline maintenance-related paths)

The followings are description of the elements of Figure (6.2) and their detail links:

6.2.1 System Risk Model

The system risk model consists of Event Sequence Diagrams (ESDs) and Fault Trees (FT). The ESDs delineate the possible risk or hazard scenarios. ESDs represent a set of possible risk scenarios where, given the occurrence of the initiating event, the state of engine (a Pivotal Event in Figure 6.3) determines whether the sequence leads to success (End State S) when the system works properly, or to a second Pivotal Event in which the flight crew action is required, when the system fails. Given the success of flight crew, the final outcome would be Success (S). The failure of flight crew leads to Failed State (F). As described in the FT, the failure of engine can be due to different types of causalities including internal causes, maintenance deficiencies, mismanagement by crew, and external factors. The maintenance related failures are the concern of this causal framework.

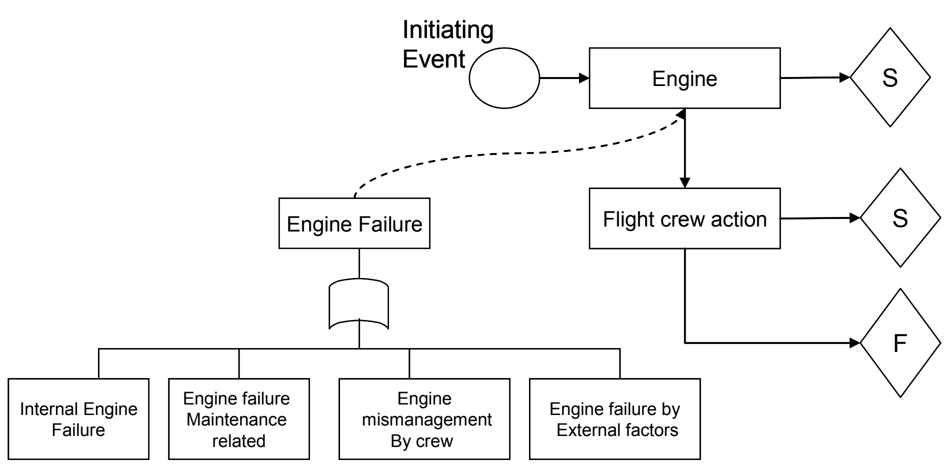

Figure 6.3 An example of technical system risk model

For the technical system failure, we used the scenarios developed by Roelen & Wever (2005). They developed aviation scenarios in five different phases including Taxi Phase, Takeoff Phase, Climb Phase, En route Phase, and Landing Phase. The following are sample failures for each phase:

- Taxi Phase
  - A. Incorrect presence of aircraft/vehicle on runway in use
    - A.1. ATC fails to resolve the conflict
    - A.2. Flight crew or vehicle driver fails to resolve the conflict
- Takeoff Phase
  - A. Flight crew fails to maintain control
  - B. Aircraft handling by flight crew inappropriate
  - C. Aircraft fails to rotate and lift-off
  - D. Aircraft stalls after rotation
  - E. Aircraft system failure
  - F. Single engine failure
- Climb Phase
  - A Flight crew fails to maintain control
  - B. Flight control system failure
  - C. Flight instrument failure
  - D. Aircraft encounters adverse weather
  - E. Flight crew incapacitation
  - F. Single engine failure
  - G. Aircraft positioned on a collision course
  - H. Cracks in aircraft pressure cabin
  - I. Flight crew decision / operation error
- En route Phase
  - A Flight crew fails to maintain control
  - B. Fire onboard aircraft
  - C. Single engine failure
  - D. Flight crew member spatially disoriented
- Landing Phase
  - A. Failure to achieve maximum braking
  - B. Cracks in aircraft pressure cabin
  - C. Flight crew decision / operation error
  - D. Thrust reverser failure
  - E. Single engine failure

A full description of all possible scenarios is available in (Roelen & Wever, 2005). The hardware failure elements (e.g., engine failure) of technical system scenarios are linked to the maintenance group performance, and ultimately to their root organizational factors that are going to be described in the next sections.

6.2.2 Maintenance Performance

This part of the model represents how well all necessary maintenance work is carried out based on manufacturers' instructions. For this purpose an aircraft airworthiness BBN (Eghbali, 2006) was used as basis for to relate maintenance-group work quality to organizational roots. Aircraft airworthiness is a Safety Critical Task (SCT). As discussed in Chapter 5, SCTs are those activities that have direct effects on the elements of technical system risk scenarios. In the example scenario of Figure (6.3), maintenance-related cause of engine failure provides the link to the rest of the risk model. In the following, we will describe various key links and factors of the model.

6.2.3. The link between Aircraft Airworthiness & System Risk Model (Link "A" in Figure 6.2)

This link is established utilizing a parametric approach, named Omega Factor (Mosleh & Golfeiz, 1999). For example, using Figure (6.3), an engine failure rate (λ_{Engine}) can be divided into four contributors: The rate of "inherent" failures (λ_I), the rate of failure due to maintenance error (λ_{MX}), the rate of failure due to mismanagement by crew (λ_C), and the rate of failure due to external factors (λ_{Ext}).

The inherent portion of the failure rate represents failure mechanisms which are beyond the control of the organization in charge of operating the airline. In its simplest form, λ_I represent the expected failure behavior as specified by the manufacturer. If there are no additional influences by the organization, no adverse external factors, and no mismanagement by crew, the component should perform according to the manufacture's expected λ_I (an exponential constant failure rate model is assumed).

A parameter ω is defined as :

$$\omega = \lambda_{MX} / \lambda_I = N_{MX} / N_I \quad \text{(Equation.6.1)}$$

where, N_{MX} is the number of maintenance related failure, and N_I is the number of inherent failure for engine.

In order to establish a relation between omega(ω) factor and maintenance performance model, P_I is defined as probability of aircraft non-airworthiness, which can be estimated from the target node of the maintenance causal model (a BBN target node). P_I could also be viewed as the probability of substandard maintenance and estimated from Equation (6.2):

$$P_1 = N_{subSTD} / N_{T\text{-}maint} \quad \text{(Equation. 6.2)}$$

where $N_{T\text{-}maint}$ is total number of maintenances performed on an aircraft and N_{subSTD} is the number of substandard maintenances. The total number of maintenance ($N_{T\text{-}maint}$) is the combination of required maintenances based on procedure (N_{maint}),and non-procedure (random) maintenance (N_{random}) . Since N_{random} is a lot smaller than N_{maint} , $N_{T\text{-}maint}$ is roughly equal to N_{maint} .

We also define P as the probability that maintenance activities result in an engine failure:

$$P = N_{MX} / N_{maint}$$

$$P = P_1 * P_2 \qquad P_2 = N_{MX} / N_{subSTD} \qquad \text{(Equation. 6.3)}$$

where, P_2 stands for the probability that substandard maintenance will result in engine failure. These equations show that P_1 and omega (ω) are proportional:

$$\omega = P_1 * P_2 * K \qquad K = N_{maint} / N_I \qquad \text{(Equation. 6.4)}$$

K is a constant design factor (e.g., a particular aircraft & manufacturer) and not related to airline, P_1 is related to maintenance organization, and P_2 represents the sensitivity of each main component to the maintenance. However, the value of P_2 is different for different main components, and thus the value of ω is specific for each main component (e.g., engine, gear). Therefore, there is a constant value (K') for each main component:

$$K' = K * P_2 = \omega_{Engine\_G} / P_{1G} \qquad \text{(Equation. 6.5)}$$

where ω_{Engine_G} is the generic value of ω for engine and can be estimated from generic failure rates. P_{1G} is also the generic value (based on data) for the probability of non-airworthiness. Based on Figure (6.2), the state of aircraft airworthiness (maintenace quality) is affected by the root organizational factors. If we change (make better/worse) the organizational factors, the new value of engine failure rate due to maintenance (λ_{MX_new}) is estimated as follows:

$\lambda_{MX\_new} = \omega_{Engine\_new} * \lambda_{I}$

$\omega_{Engine\_new} = P_{1new} * K'$ (Equation. 6.6)

where, ω_{Engine_new} is the new value of the Omega factor for engine and P_{1new} stands for the new value of P_1 estimated from new state of organizational factors. The states of organizational factors impact the value of P_1 through their effects on the factors of safety causal model (see Figure 6.2).

λ_{MX_new} is used in the fault tree in the Figure (6.3) to estimate the probability of Engine Failure, Pr (Engine). Considering the changes in organizational factors, the new value for probability of Engine Failure, Pr (Engine_new), is calculated using the Equation (6.7):

$\lambda_{Engine\_new\_} = (1+ \omega_{Engine\_new}) (\lambda_{I}) + \lambda_{Ext} + \lambda_{C}$

Pr (Engine_new)= $\lambda_{Engine\_new} * T_{mission}$ (Equation. 6.7)

where ,$T_{mission}$ stands for mission time. It should be mentioned that λ_{C} may also vary due to changes in organizational factors, but for simplicity this is not considered here. The same approach can be used to assess the effects of changes in the pilot error due to organizational factors, and estimate the new value for probability of pilot error in condition of engine failure,Pr(Pilot Error_ new | Engine failure). These probabilities are plugged into ESD in order to estimate the new accident probability, Pr (F), which is based on new states of organizational factors:

Pr (F) = Pr (Engine_new) * Pr (Pilot Error_ new | Engine failure) (Equation. 6.8)

6.2.4 Maintenance Unit Process Model

Maintenance unit process model includes the direct activities that result in quality of maintenance make the aircraft airworthiness (Safety Critical Task). Based on maintenance model developed by Eghbali (2006) the direct activities are identified as “In-house maintenance”, “outsource maintenance”, “through flight maintenance”, and “return to service inspection (RTSI)”. These activities are modeled using process modeling technique; name IDEF0 (that was explained in the Section (4.4) of thesis). Using this philosophy, any direct activity in the unit process model is affected by its direct causes including the direct resource, procedure and other human actions. Figure (6.4) presents the causal model of the maintenance unit process model. The target node of this causal model is aircraft airworthiness (maintenance quality). In other words, the state of maintenance quality depends on the states of direct activities, and the sate of direct activities depends on the state of individual’s performance, states of procedures and tools/ equipment affecting them. By procedures, we mean manuals, necessary checklists for performing maintenance tasks, and other written instructions.

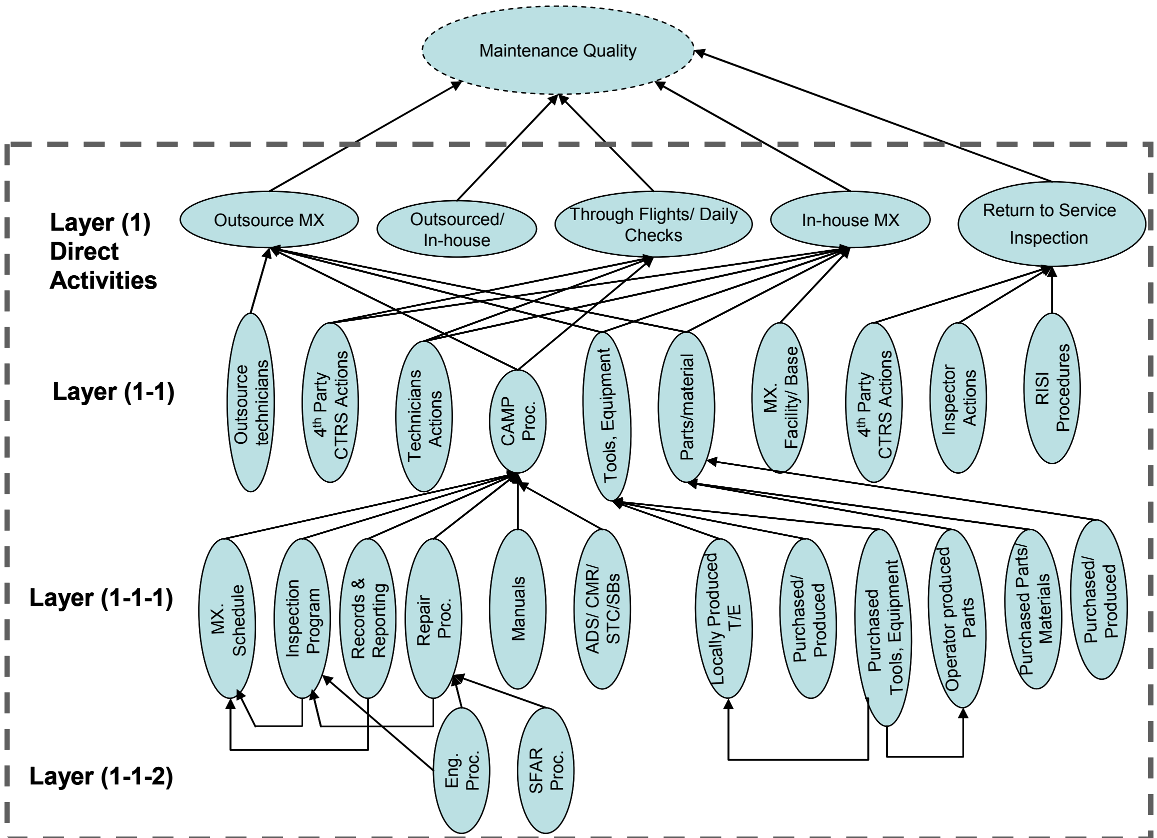

Figure 6.4 Maintenance Unit Process Model

As Figure (6.4) presents, level (1) of the unit process model include the direct activities that support maintenance quality. The factor named "outsourced/ In-house" shows the percentage of outsourcing (a managerial decision). Level (1-1) includes the direct procedures, tools / equipment, and human actions through which the direct activities are realized. For example, the direct resources for in-house maintenance are tools, equipment, parts/materials, and maintenance facilities. The direct procedure for "In-house maintenance" is "CAMP procedure". Direct individuals for "in-house maintenance" are technicians and 4th party contractors.

Next layer, Level (1-1-1), of the model includes the subdivision of *resources* and *procedures* in the level (1-1). For example, CAMP procedure is broken down into maintenance schedule, manuals, records and reporting , repair procedure, inspection program, and Airworthiness Directives/ Certificated Maintenance Requirements/ Supplemental Type Certificate / Service Bulletin (ADs/CMR/ STC/ SBs) . Also, tools and equipment are either locally produced or purchased. Pats/materials can be either operator produced or purchased. The nodes purchased/ produced shows the percentage of purchased over produced and is a managerial decision.

Level (1-1-2) of the unit process model covers the procedures that guide some of the procedure of the level (1-1-1). This includes engineering procedure, and SFAR procedure that guide the repair procedure.

The state of procedure in the model refers to procedure quality and means the extent to which procedures are in compliance with manufacturers suggested procedures and regulatory entities mandates/advisory circular. The state of resources (tools/ equipment) and human nodes include both their quality and their availability. For example, the quality of human action is the extent to which human actions are complied with air carries' maintenance procedure and /or organizational policies and government regulations and rules. The quality of tools means the extent to which the specification of the tools used in maintenance comply with the manufacturer's standards. The availability of these items is the probability of them being available when needed. The availability of direct human and resources are lumped in one factor, named "availability of resources", which influence the quality of maintenance schedule. With this approach, both the availability and quality of human and resources affect the state of the direct activities, but through different paths of influence. We refer the reader to the report prepared by Eghbali (2006) for more description of the factors.

6.2.5 Organizational Safety Structure & Practices

For structural factors, as we mentioned in Chapter 5, we have used the set of "design factor" in Mintzberg theory (1983) including the key coordination mechanism, the key part of the organization, the type and degree of centralization, formalization, specialization, and hierarchy. We used a questionnaire developed by Doty et al. (1993) to measure Mintzberg's design factor. In Section (5.9.3.2), samples of their questions are provided.

Although *organizational structure* and *organizational practices* have overlaps and are strongly interrelated, in this research we mostly cover organizational practices, acknowledging that study of the effects of organizational structure on the safety needs future effort.

As we described in the Section (5.9.3.3), organizational safety practices include all organizational practices/activities that support the resources, tools/equipment, and human actions in the unit process model that ultimately affect the safety critical tasks. For the maintenance-related causal paths, we consider the organizational practices that have effects on the maintenance unit process, and they are classified into three groups including (1) resources-related activities, (2) procedure-related activities, and (3) human- related activities. All these three kinds of activities are supported by common practices including design, implementation, internal auditing, and internal change system. (See Figure 6.5)

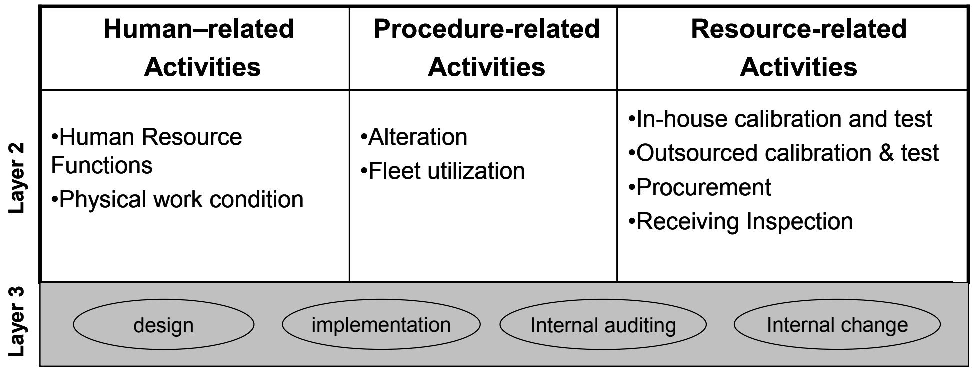

Figure 6.5 Organizational safety practices (Maintenance-specific)

All the practices/ activities of the framework (including the practices in the unit process model and organizational practices) are classified in three layers (1, 2, and 3). Layer (1) is in the unit process model that was described in the previous section. The other two layers are included in the organizational practices and are explained in the following.

6.2.5.1 Resource-related Activities

Continuing the layers in the unit process model, this part consists of layer (2) of the framework including the activities that support resources of layer (1-1-1) of the unit process model. The activity that support locally produced tools and equipments is *in-house calibration and test*, the activity that support *purchased tools and equipment* is *outsourced calibration and test*, and the activities that supports *purchased parts and materials* are *procurement and receiving inspection*. The factor outsourced/ in-house means the percentages of outsourced tools & equipment over In-house and is a managerial decision. Layer (2-1) of this part includes the resources, procedures and human actions that are needed for the activities in the Layer 2. For example, *in-house calibration and test* activity needs *technician actions*, *Master calibration and test equipment*, *calibration and test procedures*, and *4th party contractor's actions*. (see Figure 6.6). We refer the reader to the report prepared by Eghbali (2006) for description of these activities.

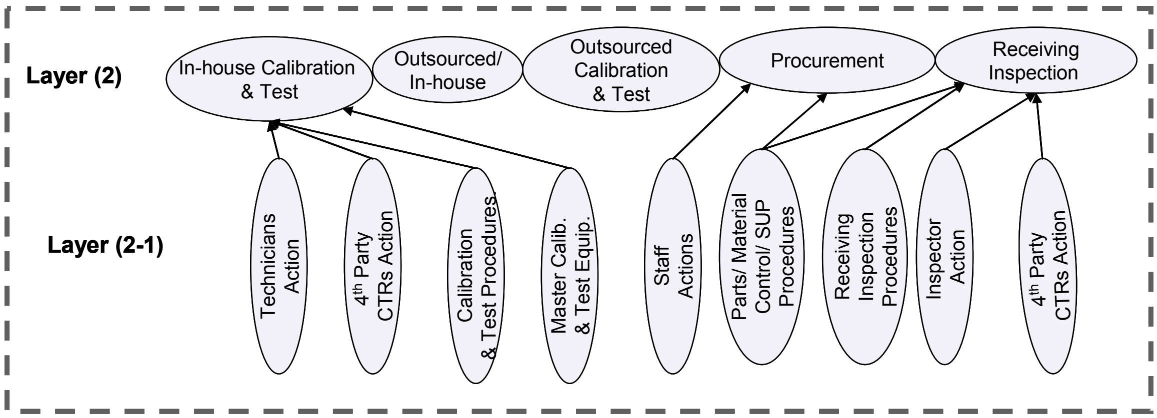

Figure 6.6 The causal paths for Resource-related Activities (maintenance-specific)

6.2.5.2 Procedure-related Activities

Continuing the layers in the unit process model, this part consists of Layer (2) of the framework including the activities that support the procedures of Layer (1-1-1) of the unit process model. The activity that supports records and reporting is alteration and the activity that support MX schedule is fleet utilization. Layer (2-1) of this part includes the procedure and human actions that support the activity in the Layer 2. Alteration activity is supported by engineering staff actions and design alteration station (DAS) & delegation option authorization (DOA) procedures. Fleet utilization is related to operation of airline, therefore, it is assumed as input to the maintenance causal model and it is not expanded in this part. (see Figure 6.7). We refer the reader to the report prepared by Eghbali (2005) for description of these activities

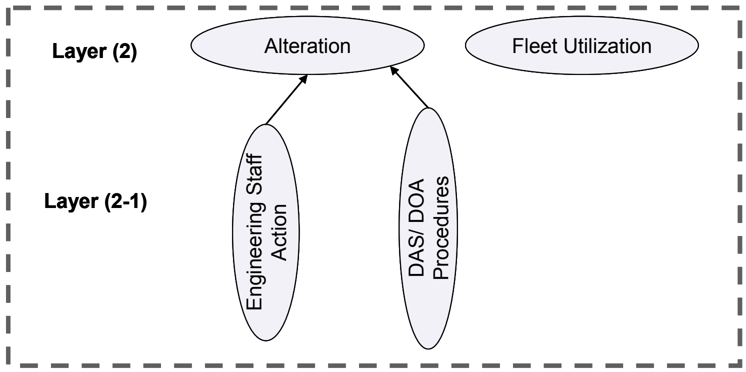

Figure 6.7 The causal paths for Procedure-related Activities (maintenance-specific)

6.2.5.3 Human-related Activities

Continuing the layers in the unit process model, this part consists of Layer (2) of the framework including all human resources practices and physical work conditions that affect human actions in the unit process model and also all human actions involved in other organizational practices (e.g., Resource-related activities). For human-related activities we used the general factors developed in Chapter 5 (see Table 5.1).

Layer 2-1 of this part should include the related resources, procedures, and human actions for the human resource functions. We have not developed layer corresponding to human resource, and future work should be devoted to this aspect.

6.2.5.4 Common Activities

This part covers Layer (3) of the framework, named *common activities*, including “design”, “implementation”, “internal auditing”, and “internal change system". (see Figure 6.5) All bottom layer "procedures" and "resources" in the framework (the procedures and resources that don't have any lower layer supporting factor) are affected by design, implementation, internal auditing, and internal change factors. Figure (6.8) shows the connections between "common activities" and "resource-related activities". Figure (6.9) shows the links between "common activities" and "procedure-related activities".

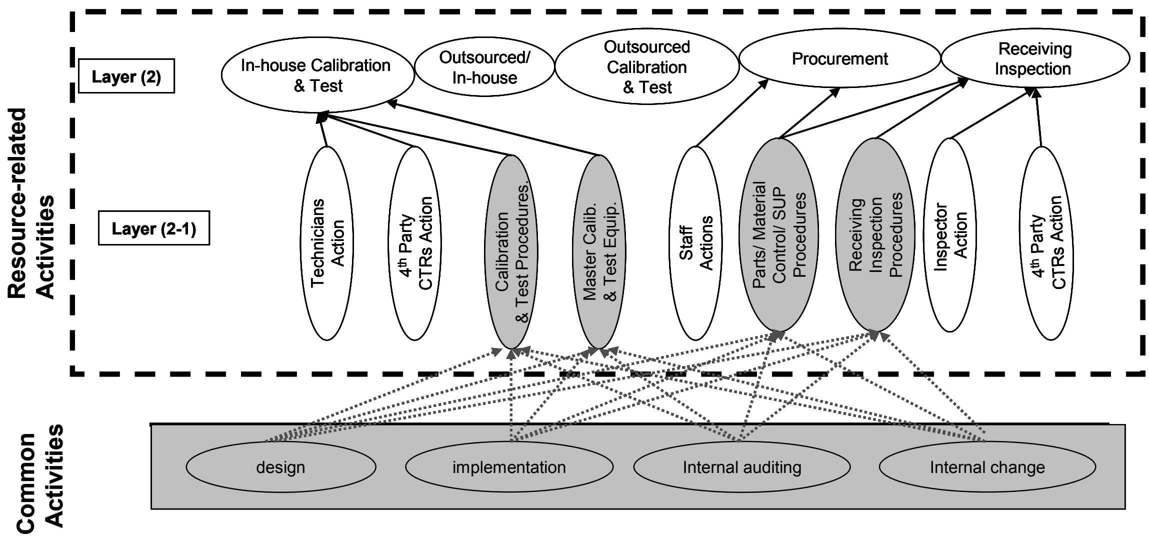

Figure 6.8 The links between "common activities" and "resource-related activities" (maintenance-specific)

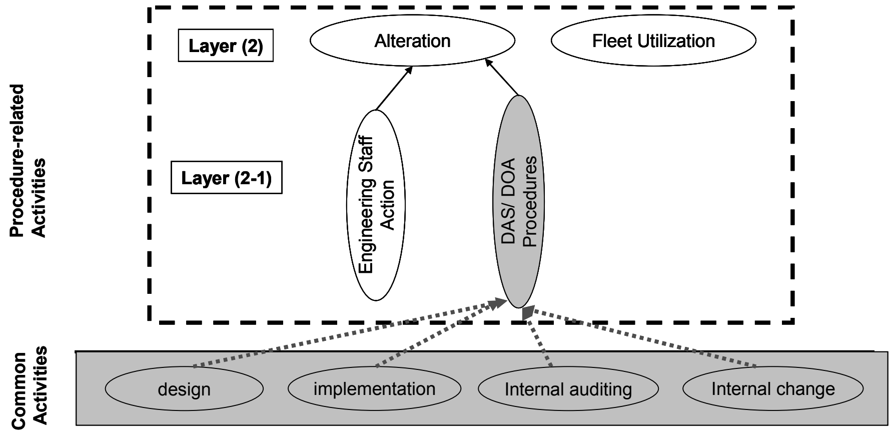

Figure 6.9 The links between "common activities" and "procedure-related activities" (maintenance-specific)

As we mentioned in the previous section, since we have not developed layer (2-1) of the human related activities, we cannot show the detail connections between "common activities" and "human-related activities".

Layer (3-1), which is not developed in this work, should include the procedure, resources, and human actions that are needed for layer 3. Like any other layer of the framework, these items can be found with developing the process model (referring to IDEF0 technique) of the factors in layer 3. For example, Continued Airworthiness Surveillance System (CASS) internal auditing system need "CASS auditing procedure", and "CASS auditing procedure" would be an element of layer 3-1. Layer (3-1) needs future effort to be expanded.

6.2.6 The Direct Link between Organizational Safety Practices and Maintenance Unit Process Model (Link "B" in Figure 6.2)

The direct link between organizational safety practices and maintenance unit process model is consisting of three types of connections:

1. The connection between “resource-related activities” and unit process model: This connection would be through the layer 2 of the “resource-related activities” and resources of layer (1-1-1) of the unit process model. (see Figure 6.10) These links are based on the relations identified by Eghbali et al. (2006)

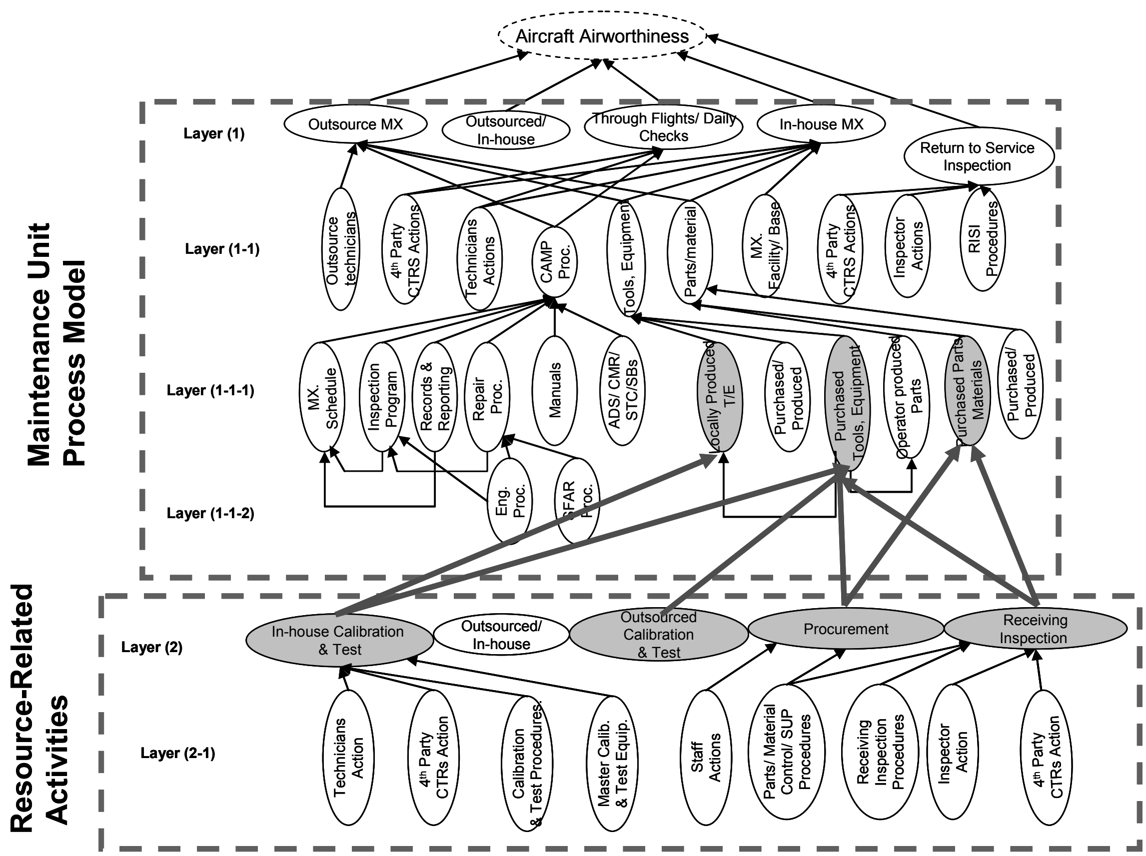

Figure 6.10 The links between “Resource-related activities” and “Maintenance unit process model”

2. The connection between “procedure-related activities” and unit process model: This connection would be through the layer 2 of the “procedure-related

activities” and procedures of layer (1-1-1) of the unit process model. (see Figure 6.11) These links are based on the relations identified by Eghbali et al. (2006).

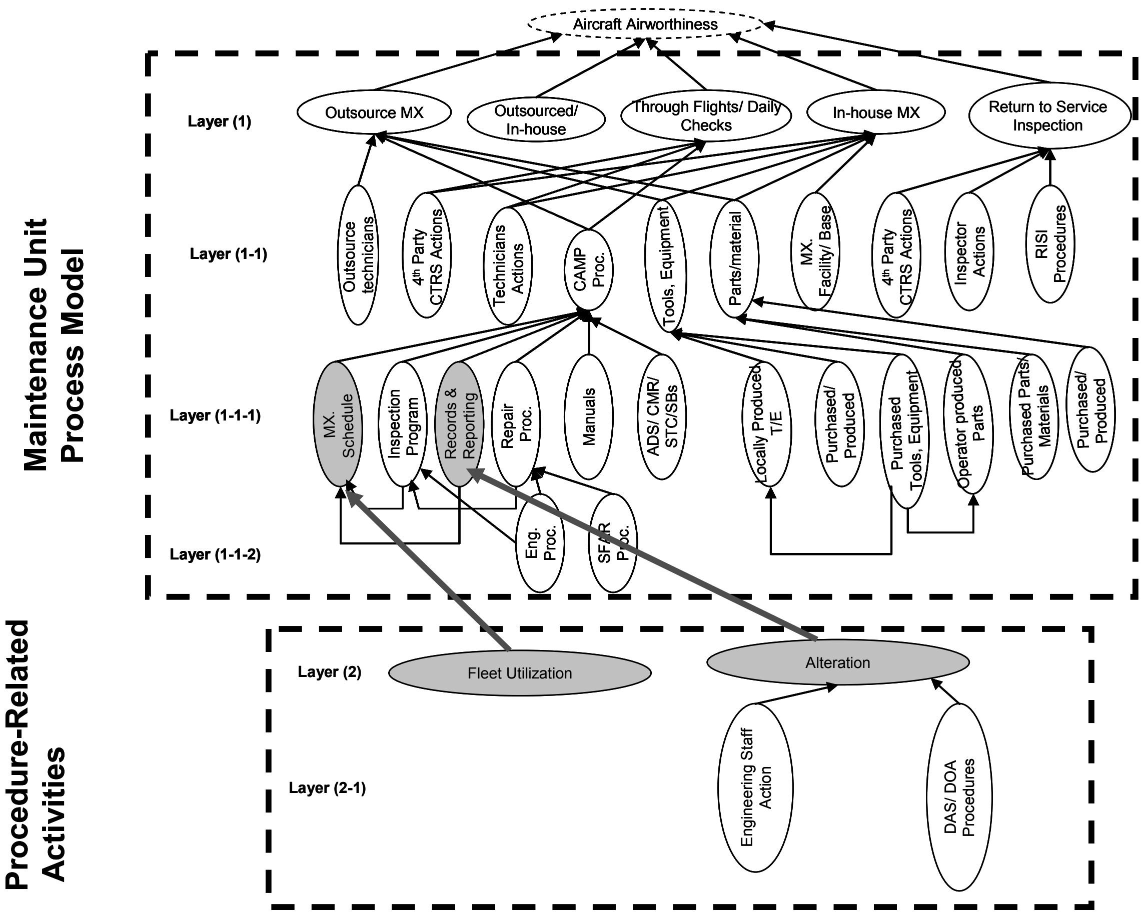

Figure 6.11 The links between “Procedure-related activities” and “MX unit process model”

3. The connection between “common activities” and bottom layer procedures and/or resources of the unit process model: as we mentioned in the previous section, bottom layer procedures and/or resources of the unit process model are the procedures and/or resources in the unit process model that don’t have any lower layer supporting

factor. (see Figure 6.12) These links are based on the relations identified by Eghbali et al. (2006).

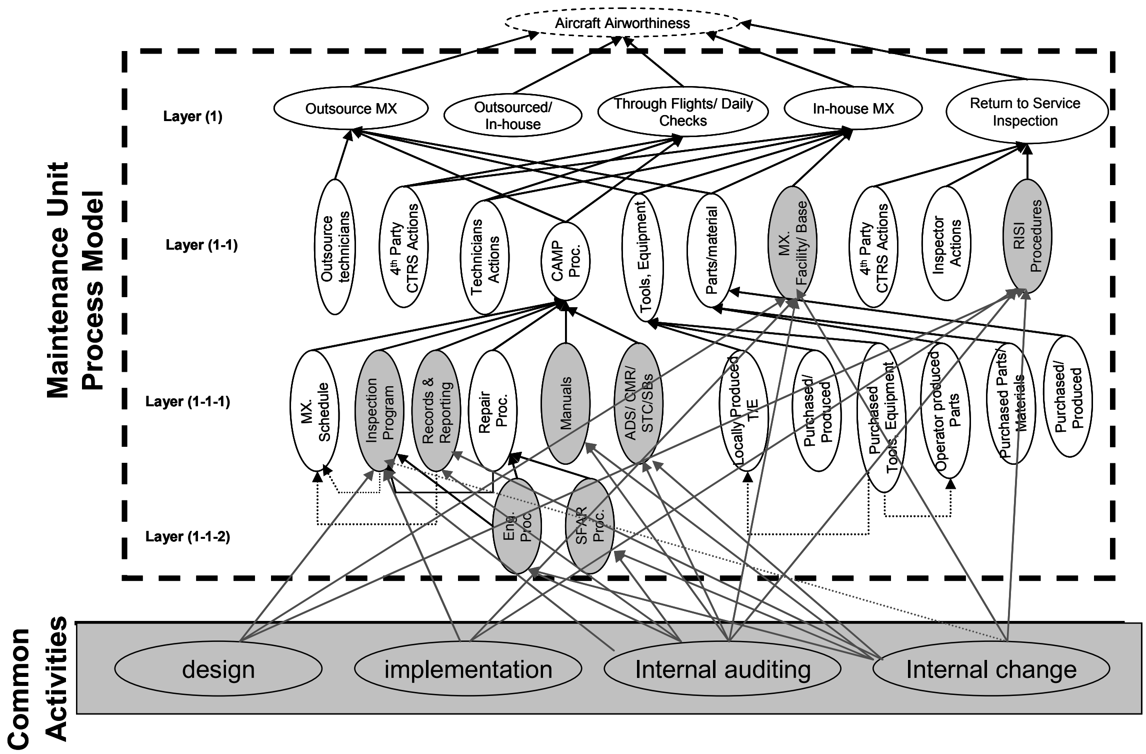

Figure 6.12 The links between "Common activities" and "Maintenance unit process model"

6.2.7 Organizational Safety Culture & Its Connection to Organizational Safety Practices (Link "C" in Figure 6.2)

Analyzing the factors developed by Gibbons et al. (2005) for the safety culture of airline maintenance organization, we found the factor "safety value (attitudes and values expressed (in word and actions) by upper management regarding safety)" to be similar to the definition of organizational safety culture in our framework. The rest of their factors are mostly safety climate and we will consider them under maintenance group safety climate (Section 6.2.10).

Safety culture shapes managerial decisions regarding organizational safety practices. The connection of safety culture with organizational safety practices is by its influences on the layer (3-1) of the framework, i.e., the supporting procedures, resources, and human actions for four practices of design, implementation, auditing, and change. For example, the quality of designers is related to managerial safety value.

Safety culture is also directly affects the managerial decision nodes such as the percentage of outsource over produced maintenance (outsource/produced) and the percentage of purchased over produced resources (purchased/produced). We use the safety culture as a barrier that eliminates the direct effects of financial pressure on the safety practices in organizations.

In this report, for simplicity, we took the "safety value" as a substitute of safety culture, but we there is a need for a more comprehensive organizational safety culture survey by adapting the methods such as Organizational Culture Inventory (OCI) and Competing Values Framework (CVF) , and Organizational Culture Profile (OCP) . (See Ostroff et al., 2003)

6.2.8 Individual-level Performance Shaping Factors (PSFs) & Its Connection to MX Unit Process Model (Link "D" in Figure 6.2)

Simplified version of individual PSFs (see Figure 4.10) consists of "motivation", "ability", "opportunity", psychological safety climate, and individual values. As we explained in Section (4.10), motivation is directly affected by psychological safety climate. Psychological safety climate which is individual's perception of safety practices, is influenced by group safety climate and personal values. Ability includes both knowledge and physical ability. Opportunity is also divided into physical opportunity (due to physical working environment such as lightning) and time opportunity (e.g., time pressure due to work schedule). In human reliability literature, physical opportunity also includes the quality and availability of direct resource and procedure for human action. But, in our framework, we separate the equality of resource and procedure from human action and the human action nodes do not cover the human error due to shortcomings in his/her resources and/or procedures. The probability of this error on the quality of any activity is considered through procedure and resource nodes. Both of these modeling views have the same philosophical ground and can be applied interchangeably. (see Section 4.9)

The connections between individual PSFs and unit process model (or organizational safety practices) are through their effects on the human actions nodes (except the contractors). Deviation of human from standard action can be in the form of error or violation (indented action). Figure (4.10) shows the connection between Internal PSFs and any human node in the framework.

Contractor's causal model is different from other human node in the framework because they are not working in the climate of the specific airline being studied. Therefore, we model these nodes simply by the effect of an item, named "contingent workforce", in the human resources factors, and do not consider the paths of safety climate and internal performance shaping factors for contractors' action.

6.2.9 The direct link between individual-level PSFs & Organizational Safety Practices (Link "E" in Figure 6.2)

Organizational safety practices have direct and indirect effects on the individual PSFs. The indirect effects are through safety climate (Section 6.2.10 & 6.2.11), but the direct effects are by the influence of "human-related activities" on the "ability" and "opportunity". For example, the quality of training and selection in an organization affects the level of knowledge, and the quality of time schedule and staffing affects time opportunity.

Table 6.1 The direct Links between "Human-related activities" and "Internal PSFs"

Individual-level PSF

Human –related activities

	knowledge	Physical Ability	Time Opportunity	Physical Opportunity
Selectivity in Recruiting/Hiring (SE)	Y	Y	N	N
Internal Staffing (ST)	Y	N	N	N
Training (TR)	Y	N	N	N
Appraisal (AP)	I	I	N	N
Reward System (RE)	I	I	I	N
Job Analysis (JA)	N	N	N	N
Team Systems(TS)	Y	Y	Y	N
Employee Assistance (EA)	N	N	N	N
Due process (DP)	N	N	N	N
Employee Voice/ Empowerment (EM)	N	N	I	I
Diversity (DI)	Y	N	N	N
Legal Compliance (LC)	N	N	N	Y
Safety (SA)	Y	N	N	Y
union Relations (UR)	N	N	Y	Y
Job Enrichment (JE)	Y	Y	Y	N
Contingent Workforce (CW)	N	N	Y	N
Physical Work Condition (PWC)	N	N	N	Y

Table (6.1) shows the factors in "human-related activities" that have direct effects on Individual PSFs (sign Y stands for "direct relation", sign N stands for "no relation", and sign I stands for "indirect relation"). The support for these relations are scattered in different psychology literature, but here we relied on Ostroff(1995), and separately eliciting her judgment . A more detail analysis of these relations needs future research.

6.2.10 Maintenance Group Safety Climate and Its Links to Internal PSFs (Link "F" in Figure 6.2)

For the maintenance group safety climate, we use the factor developed by Gibbons et al. (2005), except the "safety value". We also changed "organizational commitment" to "routine system" that covers the individuals' perception regarding training, work environment, work schedule, and corresponding resources. Figure (6.13) shows maintenance group safety climate and its link to internal performance shaping factors. The climate contents are presented in the figure, but we refer the readers to Gibbons et al. (2005) for their complete descriptions. (see Appendix B)

Because of the importance of supervisors and their impacts on the other elements of climate, we give the group safety climate factors two layers. The bottom layer is the factor, named "supervisors", which influence the factors of the upper layer. Supervisor's effect is not only directly an element of group safety climate, but also they have impacts employees' interpretation of other aspects of organizational practices. As Ostroff et al. (2003) describe, leaders and supervisors function as interpretive filters of organizational practices for organizational members. For example, the antecedents of employee's perception about "training" are both "actual quality of training" in organizational practices and "supervisors' attitude toward training.

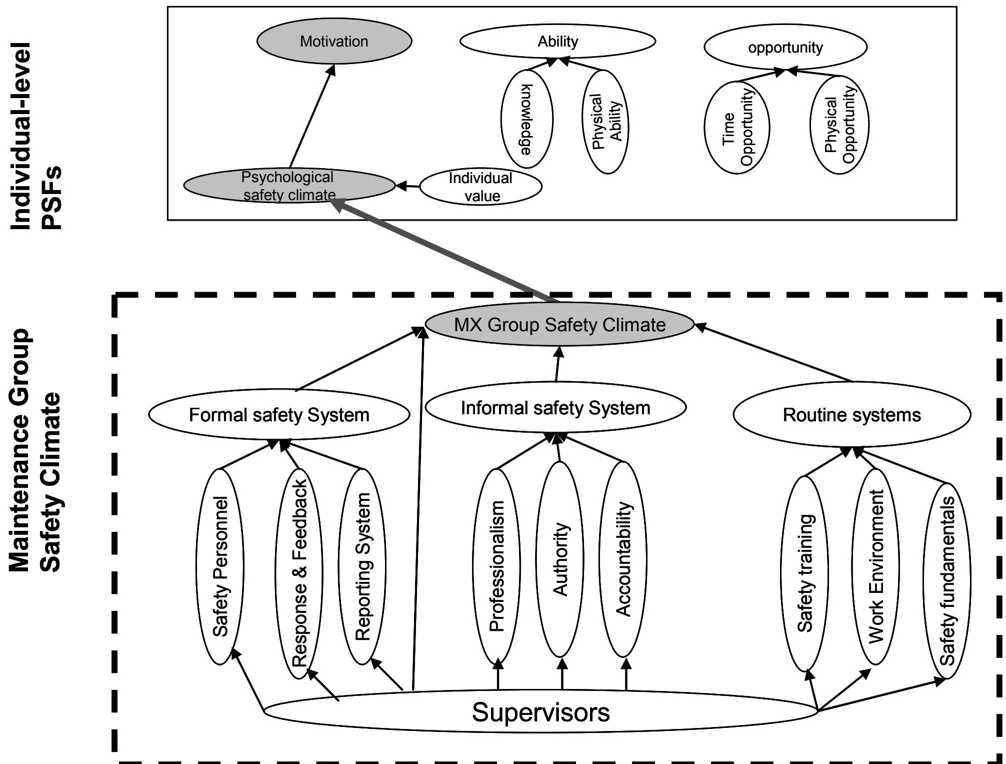

Figure 6.13 MX Group Safety Climate and its link to "Individual-level PSFs"

As it was explained in Section (5.10), *group safety climate* affects *psychological safety climate* and ultimately *motivation* in the individual-level PSFs. *Psychological safety climate* includes the same factors of group safety climate, but is measured at the level of individual.

As a complementary point, we need to mention that group climate for technicians are different from group climate for staffs or inspectors. The elements of climate are the same, but perception survey should be filled with different employee to measure the related climate. In the causal model, it would affect the strength of the links.

6.2.11 The Link between Organizational Safety Practices & Maintenance Group Safety Climate (Link "G" in Figure 6.2)

The link between organizational safety practices and the contents of group safety climate are built by making connection between human-related activities and the content of group safety climate. For example, the actual quality of training has effect on the employee's perception about training. This perception is also affected by supervision (an element of emergent process).

Table 6.2 The links between organizational safety practices & maintenance group safety climate

Group safety Climate Elements

Human Related-Activities

	WE	SF	ST	SU	AC	AU	PR	RS	RF	SP
SE	N	N	N	N	N	Y	N	N	N	Y
ST	N	Y	N	N	N	N	N	N	N	N
TR	N	N	Y	Y	N	Y	Y	N	N	Y
AP	N	N	N	Y	Y	Y	N	Y	N	Y
RE	N	N	N	N	Y	Y	N	N	N	N
JA	N	N	N	N	Y	Y	N	N	N	N
TS	N	N	N	Y	Y	Y	N	N	Y	N
EA	N	N	N	N	N	Y	N	N	N	N
DP	N	N	N	N	Y	N	N	Y	N	N
EM	N	N	N	N	Y	Y	Y	Y	N	Y
DI	N	N	N	Y	Y	N	Y	N	N	N
LC	Y	N	Y	Y	N	N	Y	Y	Y	N
SA	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
UR	Y	N	Y	Y	Y	N	Y	Y	Y	N
JE	N	N	N	N	N	N	N	N	N	N
PWC	Y	N	N	N	N	N	N	N	N	N
CW	N	Y	N	N	N	N	Y	Y	N	N

Table (2) presents the causal connections between human resource activities and maintenance group climate. These relations are built based on analysis of the description of human resources practices (Appendix A) and the content elements of safety climate adapted from Gibbons et al. (2005) (Appendix B). Expert judgment has been used for some of the justifications.

The abbreviations used for the factors of Table (6.2) can be found in appendix A and B. “Y” refers to the presence of relation. For example, the table shows that empowerment as a practice of human resource influences accountability (AC). More specifically empowerment affects employees’ perceptions about accountability. “N” stands for no relation.

6.2.12 Emergent Processes & Their Links to the Framework (Link “H” & “I” in Figure 6.2)

There are three possible links between emergent processes and the other parts of framework. The first one is the link between emergent process and group safety climate. As mentioned in the Section (5.9.2), emergent process factors including supervision/leadership, social interactions, and homogeneity are antecedents of climate. Figure (6.14) represents the relation between emergent process and group safety climate. Supervision in the emergent process affects the perception of employees about supervisors (an element of group safety climate). The other two emergent process factors affect all elements of group safety climate and create relate to the strength of shared perception regarding those aspects.

The second link of emergent process with other elements of the framework represents the effects of human resources on the emergent process, as depicted in Figure (4.7).

The third potential link of emergent process represents the possible direct effects of supervision on the opportunity (an element of individual PSFs). This link is not shown in Figure (6.2) in order to keep the figure simple .For example, time pressure can be due to supervisors' attitudes and/or human resource function. Zohar & Luria (2005) have argued that the procedural formalization in organization limits supervisory discretion. Therefore, the strength of direct effects of supervision on individual PSFs depends on the level of formalization in the organization.

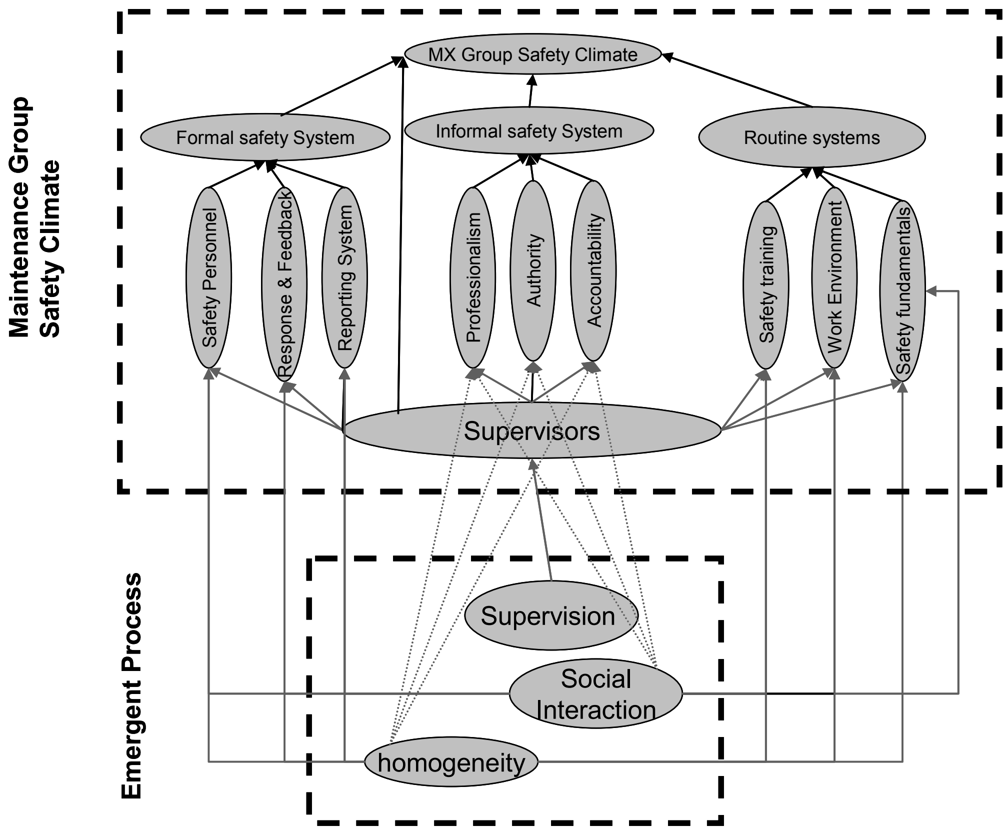

Figure 6.14 The link between "emergent process" & maintenance group safety climate

6.2.13 Regulatory Auditing System & its Link to the Framework (Link "J" in the Figure 6.2)

Regulatory effect is either through policies and standards or through the quality of the auditing system. In the present framework only the auditing aspect is considered. Regulatory auditing in aviation is a three-stage task and consists of:

a) SAI (Safety Attribute Inspection): assessing whether the safety policies are in compliance with regulations, and whether organizational practices are designed based on safety policy;

b) EPI (Element Performance Inspection): assessing whether organizational performance practices are implemented based on designed statements;

c) RE (Reporting): reporting the detected deficiencies in a timely and effective manner.

Looking at the SAI and EPI documents, we have noted that some of the procedures and resources such as manuals, inspection procedures, calibration and test procedures, and tools/equipments are directly audited by FAA, and thus there should be some direct links between regulatory auditing system and those elements. Others such as engineering procedures, repair procedures, purchased parts and materials are not audited directly by FAA, and are only audited internally by airlines.

6.2.14 Financial Effects and Feedbacks (Link "K" & "M" in Figure 6.2)

Most studies have been devoted to the effects of culture on the financial performance (e.g., Siehl and Martin, 1990), leaving the impact of financial performance on culture relatively explored. Some researchers have investigated the existence of a possible correlation between financial wellbeing of a firm and the safety performance of firms.

Like any private enterprise, though, an airline has to generate revenues in order to stay in business and even to plan for offering safe service. With that in mind and considering the fact that being safe naturally costs the airline, if an airline appears to be profitable does it mean that it is safe? Will a safer airline attract more travelers and be at a better financial standing? Are people aware of the level of the safety of airlines in the market and do they consider this in their decision making about transportation? Is the history of financial performance a strong predictor of its safety in the coming years? Is the history of safety a predictor of their financial wellbeing in future? Although some of these questions might seem to be trivial, researchers have struggled to provide answers. The results in the literature range from no relationship between finances and safety to strong correlation between the two. The spread of the results in this area alone emphasizes the importance of investigating the interactions of financial status of an airline and its safety.

We tried to collect all the factors that different research works in aviation domain, have pronounced as important. Finding the most representative ones and determining the best method of analyzing the existence of correlation between such factors and safety culture is outside of the scope of this thesis. Future research need to be devoted to this topic.

D. Golbe(1985) has studied the relationship between profitability and safety in airlines using data from US airline industry. She examines the statement in a US civil aeronautics board report expressing the concern that “in the absence of countervailing measures, removal of entry and price controls would be likely to degrade safety. Any serious financial difficulties would be conducive to a deterioration of safety." She argued that the firm maximizes utility by choosing expected profit and safety. However, neither expected profits nor safety is directly observable. Realized profit is used as a substitute for expected profits and total number of incidents is as a substitute for the firm's safety. The model is thus the system of structural equations:

$$profit = f(Incident, x_1)$$

$$incidents = g(profit, x_2)$$

where x_1 and x_2, are measures of exogenous variables that determine profit and incident rates. Golbe then proposes a model of a set of two cross-section equations, and as a measure of safety chooses the square root of the total number of incidents. The factors involved in her model are: total number of incidents, load factor, stage length (miles), number of departures, and net income or rate of return (as a measure of profitability).

Golbe then performs regression once on two separate groups of data on domestic flights in the US from 1963 to 1966 and from 1967 to 1970 to look for the possible effects of changes in technology. She also performs a regression on domestic flight data from 1952 to 1970. She claimed that the evidence on airline safety and profitability does not support the popular wisdom and no statistically significant relationship seems to exist between safety and profitability. She also indicates that there is even a weak negative relationship between the two, that is, more profitable airlines may have more accidents.

It is worthwhile, however, to note that the profits of the airline in a year have been regressed against the accidents of the same year. This might lead to incorrect interpretation, since there is probably a delay between the onset of financial troubles and effects on the operations and safety.

Noronha and Singal (2004), explored how financial distress could lead to riskier strategies in an airline. They, too, ran a regression on an equation to examine the relationship between the frequency of mishaps and the financial situation of the airlines. As a representative of financial status, they have picked the bond quality of the firms and have given those letter grades, cardinal values. The regression has been conducted on data from major airlines only and covers years 1983 to 1998 in three 5 year periods. The factors in their model are: bond rating, number of departures, passenger miles, and number of incidents**.** They did not considered incidents due to causes such as airport congestion and severity of weather because of data limitation. Their finding supports the idea that the financial health of an airline affects its ability and willingness to provide safety and financially stronger airlines are significantly less at risk than weak ones.

Financial characteristics and its impact on airline safety in Taiwan is the subject of work by Wu et. al (2002). They believe that poor financial conditions may weaken the airline safety in two ways. First, airlines may cut off the investment budget. They claim that, although under-investment or under-profitability may not directly undermine the airline safety, enough investments or excellent profitability will directly influence the safety environment through good training facilities and sufficient logistics. Secondly, there is a rather strong incentive to decrease the expenditure of crew training and maintenance for unprofitable airlines in a short term. They believe that financial distress might cause the firms to pursue riskier strategies. For this study they have categorized financial ratios to reflect six categories of: 1- Short-term liquidity; 2- Capital structure; 3- Long-term solvency; 4- Return on investment; 5- Asset utilization; and 6- Operating performance.

The factors (variables) in this model are: current ratio, quick ratio, debt ratio, permanent capital to fixed asset ratio, return on assets, return on equity, operation revenue to total assets ratio, operation assets to fixed asset ratio, operating income ratio, and net income ratio. The authors rank each variable from 1 to 8, from the best to the worst, and use the Overall Concordant Order Ratio (OCOR) and Marginal Order Ratio (MOR) developed by Chang et. al (2000) to measure the overall ranking of the financial performance of airlines. Their conclusion potentially supports the link between financial conditions and safety.

The brand name effect of airline crashes has been studied by Maloney (2000). In this paper, in contrast with the above mentioned papers, the effect of accident (safety) on the reputation of the airline and its financial situation is of interest to the author. Even though the airlines would not suffer from loss of a plane and liability claims, since they are fully insured, but in cases where airline is at fault in an accident, the study shows that there is a significant negative stock market reaction to the event. But this negative effect does not occur if there is less reason to suspect that the airline shirked its responsibilities. Accidents will also cause an increase in insurance rates which increases the cost of airline's operation and will draw customers' attention to the higher probability of accident in that airline. The results here support the idea that customers do indeed avoid riskier airlines. Another interesting finding of this paper is that it finds no evidence of deregulation in the pattern of brand name effect. Since the market is efficient and punishes the airline responsible and at fault for an accident, the study claims that the need for increased airline safety regulation is not apparent.

Squalli (2004) examines the effect of safety and accidents on customers' reaction towards an airline and demand. First it is stated that carriers' accidents lead to a generalized fear of flying. This may indicate that when accident happens consumers do not feel immediately safer by switching to other carriers. There is also no statistical evidence that large airlines would want to vary their fare in response to a recent accident.

But small carriers tend to lower their fares in reaction to their own accidents. On the other airlines would charge higher when their rate increases.

In terms of demand and financial loss, the aggregate impact of accidents on large carriers' enplanement is 3% of their quarterly enplanement and 1.8 million passengers which is equal to $284 million in revenue losses in the quarter following the accident and no sign of recovery during the following four quarters. This study also investigates if people recall the accidents or partially remember them, or forget about accidents completely and consider them as totally random events and forgive the carrier. Factors in this study are: passenger enplanement, average ticket fare, total operating expenses, crashes, fatalities, bankruptcies, bond rating, mergers and acquisitions, average industry fare.

A model has been presented by Hartmann (2000) that estimates how accidents affect consumer purchasing behavior and how this influences airline's provision of maintenance. This study models consumers as utility maximizers and firms as profit maximizers. It concludes that information disclosed by accidents influences the competitor carriers' demand as well as that of the carrier involved in the accident. Moreover, overall industry demand is more sensitive to changes in safety provision by less safe carriers than changes in overall industry safety provision.

Naturally, it seems intuitive and trivial to think that safety and financial health of any organization that offers any service, including airlines, go hand in hand. However, one study (Golbe, 1986) indicates otherwise. As mentioned before this study has missed the concept of delay that exists between the appearance of financial distress and risky behavior of airlines. Generally the works presented fall in one of the two categories: 1) exploring what happens to the airline's safety policy and concerns and its risk level if the firm is financially in trouble, and 2) exploring what happens to the airline's financial standing if an accident happens in that carrier or another carrier, given that the airline is at fault for that accident or not.

Exploring all afformentioned references, the potential financial factors in the safety framework in aviation context would be:

- Total number of incidents
- Load factor
- Stage length (miles)
- Number of departures
- Net income
- Rate of Return
- Bond rating
- Number of Departures
- Passenger mile
- Number of incidents

- Current ratio
- Quick ratio
- Debt ratio
- Permanent capital to fixed asset ratio
- Return on assets
- Return on equity
- Operation revenue to total assets ratio
- Operation assets to fixed asset ratio
- Operating income ratio
- Net income ratio
- Passenger enplanement
- Average ticket fare
- Total operating expenses
- Crashes, Fatalities
- Bankruptcies
- Bond rating
- Mergers and acquisitions
- Average industry fare

To our knowledge there has not been a study that carefully looks at the interactions of these two terms (safety and financial performance) in a dynamic environment. A couple of the questions that are to be answered with further studies, in our view could be:

1. How long does it take before a sign of a financial distress affects the safety policies and safety culture?

2. How long does it take before an incident or accident can shift the firms' financial situation?

3. What magnitude of financial difficulty can create change in the risk level of an airline?

4. How severe of an accident can affect airline's financial wellbeing?

6.2.15 Weather Conditions (Link "L" in Figure 6.2)

Weather conditions affect the physical environment of the aircraft and also affect crew decision-making. In other words its effects are on the system risk (hardware) and the human in the operation path (not the human in the maintenance path). Its connection to the technical system risk model is through its influence on the system failure rate due to external factors (see fault tree in the Figure 6.3). Roelen & Wever (2005) include the weather condition factors including weather observation source, visibility, wind, and precipitations in the aviation risk scenarios. Weather observation source is the source that the crew consulted to receive weather information. Visibility is provided in miles. Wind is provided as a speed in knots and a direction in degrees. Precipitation is indicated as either none, rain, freezing rain, sleet, snow, hail, or mixed. Intensity is indicated as low, moderate, or heavy.

6.3 An Example Application of Hybrid Technique: Integrating "STELLA" & "IRIS" in Aviation Context

In this section, a simplified version of the causal model, described in the Figure (6.2), is used to demonstrate the application of a hybrid technique (see Section (4.10)). The main objective of this section is to show how an example of a hybrid technique can practically operationalize the organizational safety theory.

Integration of STELLA (a system dynamics software) and IRIS (a risk analysis software produced in Center for Risk & Reliability) provides this hybrid environment. IRIS is a combination of BBN, ESD, and FT techniques. STELLA has been linked to IRIS in order to empower it with System Dynamics (SD) capabilities.

SD is added to the bottom layer of the risk model (see Figure 6.15) to depict some deterministic and dynamic causation mechanisms. SD is a deterministic tool and its combination with BBN adds a stochastic dimension. This integrated software has been utilized to analyze the dynamic effects of organizational factors on system risk.

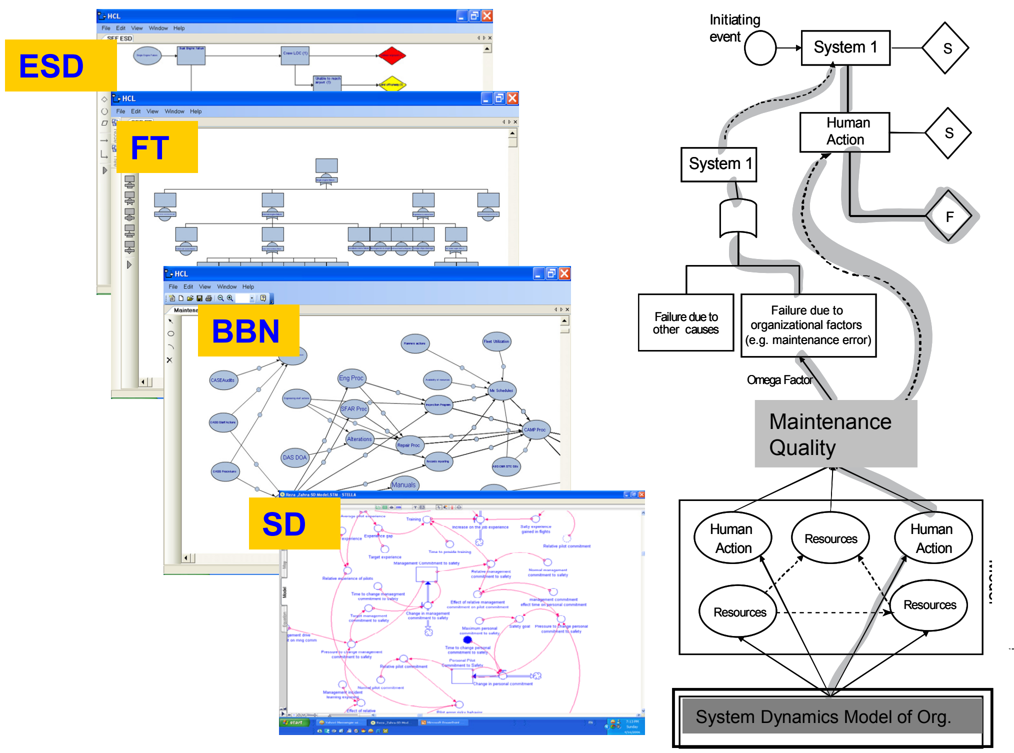

Figure 6.15 Integration of STELLA and IRIS

The following briefly describes how different elements of Figure (6.2) are implemented in STELLA and IRIS environments.

6.3.1 Organizational Safety Culture in SD Environment

In Section (6.2.7), we explained the safety culture factor and its link to the aviation model. Here, for simplification “management commitment” is considered as a measure of safety culture. Management commitment shapes the managerial decisions regarding organizational safety practices. In this model, we only connect management commitment to safety practices, “training’ and “hiring”, in order to run the example.

The management commitment module of the model illustrates important feedback loops that rule the dynamics affecting management’s commitment to safety. Naturally, management should balance priorities between safety and profitability of the airline. One possibly is that financial pressure may reduce the relative importance that managers give to safety, which eventually leads to the lowering of technicians’ commitment to safety (see Section 6.3.4). In Figure (6.16) financial priority exponent indicates the degree of influence that safety has on management commitment changes.

Since technicians will try to meet the service expectations imposed by management, they will respond to low management commitment to safety by skipping the procedures or perform them in a substandard manner, and in general more risky behavior to meet the deadlines and the schedule set by the management. As a result there will be an increase in incident rate and human error probability.

This, on the other hand is balanced by the way increases in incident rates increase management’s commitment to safety. A change in management commitment to safety is a function of deviation of safety output from normative safety level. Normative level of safety is usually set by regulators or social and cultural standards. Similar to the financial loop discussed above, in Figure (6.16), safety priority exponent indicates the degree of influence that safety has on management commitment changes.

The two exponents including safety and financial priority exponents refer to the efficacy of *organizational double-loop learning* process that is mentioned in the Section (5.12).

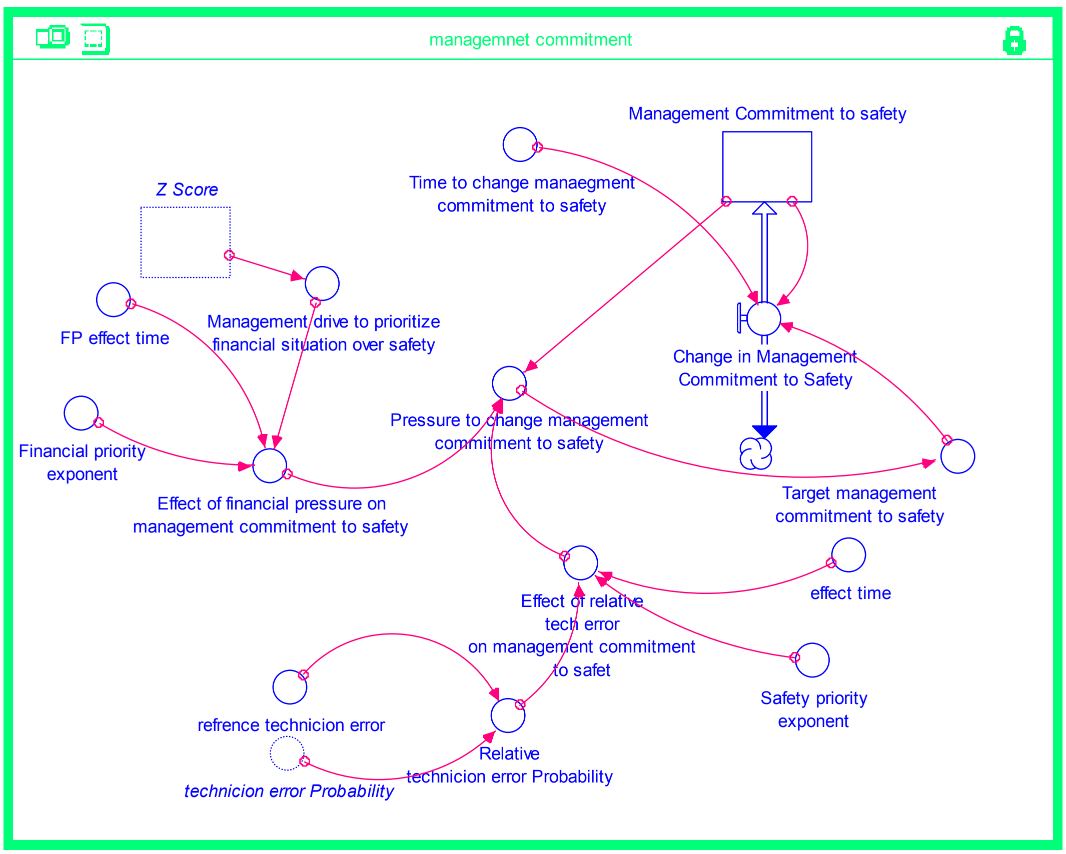

Figure 6.16 management commitment module in SD environment

Cooke (2004), constructed a management commitment module designed for mine industry, and the present module is a modified version that captures the effect of financial state (of the airline) as well. The basic modeling idea of "safety commitment" in SD, follows the concept of "sea anchor and adjustment" by Sterman (2000). It describes the process of 'groping" towards a proper quantity. It assumes a certain level of commitment for managers and technicians as a starting point, which changes according to pressures (safety and financial states) that are applied to the organization. A complete list of equations used in this module is provided in Appendix C.

6.3.2 Financial Stress in SD Environment

The idea of the financial subsystem is to demonstrate how financial distress affects safety culture and how safety output impacts financial wellbeing. One possibly is that as an organization faces a financial distress, the management intuitively concentrates on service and increasing the turn over. This might translate into a lower level of safety commitment which means less attention to training and more time pressure on maintenance technicians that leads to higher error probabilities by the technicians and finally higher risks. But this immediate solution ignores the fact that higher risk and higher incident rates in an airline will ultimately affect market's perception of the airline and result in deeper financial distress.

Section (6.2.14) discussed the financial effects and feedbacks, and provided a set of factors suggested in the literature. The financial distress subsystem has been constructed based on Albert Altman's Z score model (1968). Z score model contains a combination of some of those factors. Altman's model suggests that a "Z" score that consists of a linear combination of a set of financial ratios available on a firm's balance sheet can be a representative of the firm's financial standing. The model introduces the following factors as the best indicators of financial status:

$$x_1 = \frac{working \quad capital}{total \quad asset}$$
$$x_2 = \frac{retained \quad earnings}{total \quad asset}$$
$$x_3 = \frac{earnings \quad before \quad taxes}{total \quad asset}$$
$$x_4 = \frac{market \quad value \quad of \quad equity}{total \quad liabilities}$$
$$x_5 = \frac{sales}{total \quad asset}$$

(Equation 6.9)

The Z score is:

$$Z = 1.2x_1 + 1.4x_2 + 3.3x_3 + 0.6x_4 + x_5$$ (Equation 6.10)

This model is applicable to firms that are publicly traded, otherwise a modified version of the model need to be used. According to this model, if the Z score is less than 1.81, the firm is facing a financial distress the following year with a probability of 95%. Z scores between 1.81 and 2.67 are of concern but not threatening and above 2.67 raises no concern about the financial stress.

This model has been incorporated in the financial distress subsystem in order to capture the organization's behavior when facing a financial situation (low Z scores). The stress will cause management to ultimately be distracted from the safety concerns, concentrating on recovering balance sheet figures. Lower management commitment level to safety will result in lower technician commitment to safety, and higher incident rates, substandard training and higher technician error probability, which increases accident risk. This will affect consumers' perception of the airline safety and affect its sales and the firm's market value of equity directly and will lower the Z score and pushing the airline towards a more distressed financially distressed situation. Clearly, accidents or incidents also damage or destroy airline's assets as well.

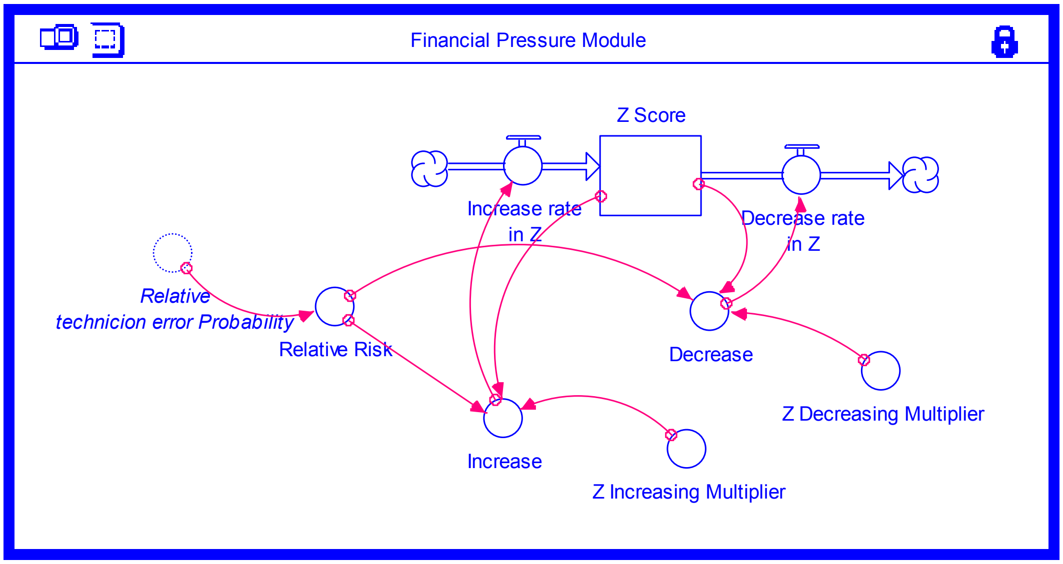

Figure 6.17 Financial pressure module in SD environment

The structure of equations that shapes these changes is provided in Appendix C. The multipliers in this module are assumed values. More realistic values require empirical studies.

6.3.3 Organizational Safety Practices in IRIS & SD Environment

In Section (6.2.5), we classified organizational safety practices into: "human-related activities", "procedure-related activities", "resource-related" activities, and "common activities". In this example, we select "training" and hiring" for human related activities. The maintenance procedure- and resource-related activities are all covered in this model. From common activities, we only include internal auditing factors in here.

6.3.3.1 Modeling Training in SD

This subsystem is intended to capture the way the experience level in an airline changes. Attrition, rookies or senior technicians, reduces the average experience in the maintenance department and hiring and training adds to it. Technicians also gain experience on the job. The level of training and its quality are also a managerial decision and is affected by the management commitment to safety. The goal is to fill the gap that exists between the level of experience needed in the organization (Target experience in Figure (6.18)), and the level that currently exists at any time. Less commitment to safety obviously decreases the level of training and therefore the amount of experience in the airline which could lead to higher probability of technician error. There is also a time lag involved in the training process that has been considered in this module. (Cooke, 2004 & Sterman, 2000)

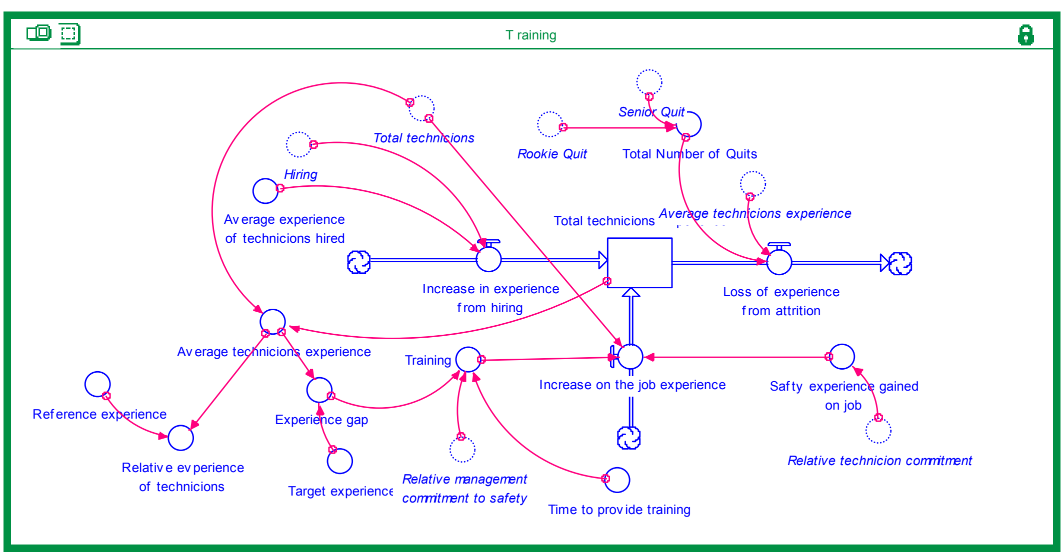

Figure 6.18 Training module in SD environment

The equations used in constructing this module are listed in Appendix C.

6.3.3.2 Modeling Hiring in SD

Cooke (2004) illustrated hiring relations in the mining industry. Mc Cabe(1998) has also presented similar relations for airline employees. Our module and its equations are modified from these two models.

The hiring subsystem describes the process of hiring rookie maintenance technicians, and their transition to experienced technicians. In this process some technicians including rookies and seniors quit the organization for different reasons (for example, poor work condition, excessive workload resulting from financial pressure, and lack of management's commitment to safety, and technician's lack of commitment to safety).This is shown as "quit rate" in Figure (6-19). Hiring has been defined as a process of trying to reduce the gap between the existing total number of technicians in the organization and the number of technicians required to fulfill the maintenance tasks, according to the market or regulating demands on the airline (Target technician demand, in Figure (6.19)). On the other hand, hiring is a managerial decision, and hence depends on the level of management's commitment to safety. It is management's decision to hire and train more people to meet the demand or place more pressure on the existing work force. There is also a time lag associated with the hiring process that has been considered in the subsystem. The outcome of the module is the total number of technicians in the system which will be used in training module. (Mc Cabe, 1998 & Cooke, 2004)

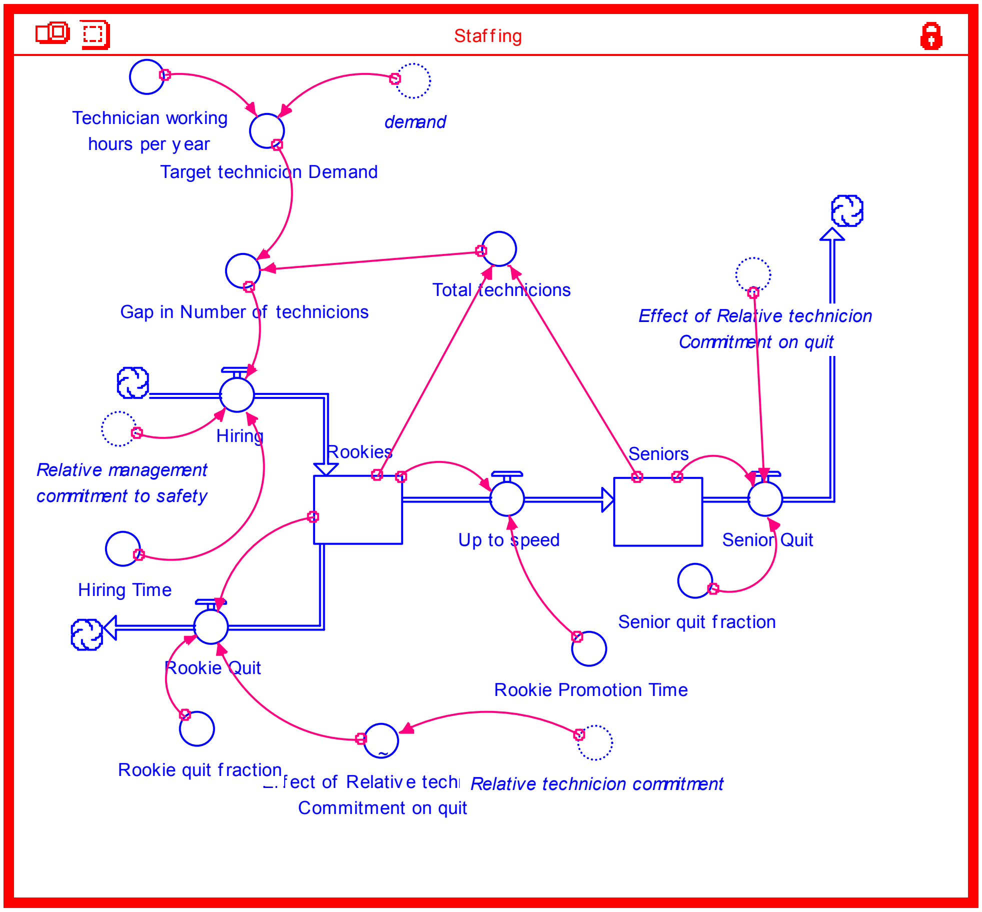

Figure 6.19 Staffing module in SD environment

The list of equation in this section is provided in Appendix C.

6.3.3.3 Modeling other organizational safety practices & regulatory auditing factors in IRIS

In the organizational safety practices categories, training and hiring are molded in SD. For the rest of organizational safety practices including resource-related activities, procedure-related activities, and internal auditing activities, we have used a (static) probabilistic model in form of BBN. As we explained in Chapter 4, in the case that we don't have explicit knowledge about the relations between the factors, the probabilistic model is more appropriate. This example represents the feasibility of combining of these two tools.

The factors described in the Sections (6.2.5.1) and Section (6.2.5.2), (the internal auditing activities and external regulatory auditing factors), are entered in the IRIS in form of a BBN model. These factors will be connected to the BBN representation of a "maintenance unit process model" that will be explained in the Section (6.3.5).

6.3.4 Individual-level PSF in SD Environment

In Section (6.2.8), the individual-level factors including psychological climate, motivation, ability and opportunity are described. Here, we designed "Human Reliability" module (Figure 6.20) to assess technicians' error probability as a function of its individual-level PSFs .

In the "Human Reliability" module, for "ability", we considered "knowledge" to be equivalent to level of experience, which is imported from the of training module. For opportunity, we selected "time pressure", which is a function of demand and the number of technicians taken from "hiring" module.

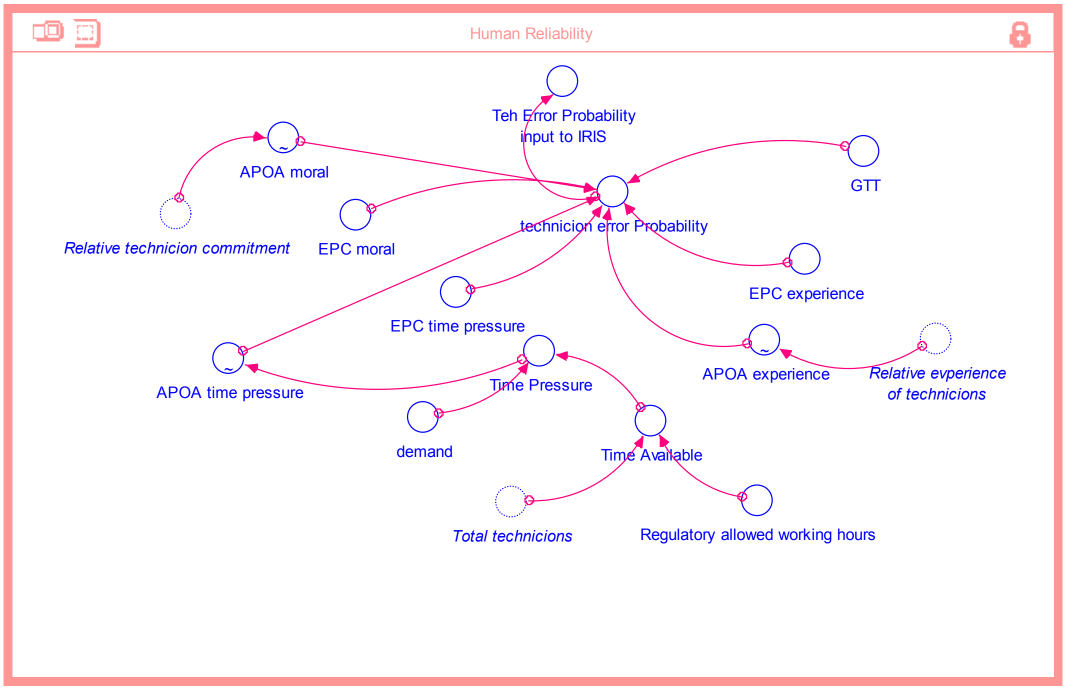

Figure 6.20 Human reliability module in SD environment

Base on Section (6.2.8), motivation is affected by psychological climate and group climate. Here, we have not modeled the psychological climate and group climate explicitly. To execute the example model, we considered a term "technician commitment", which is directly affected by management commitment. Figure (6.21) shows the 'technician commitment" module which is a modified version of Cooke's (2004) mining model.

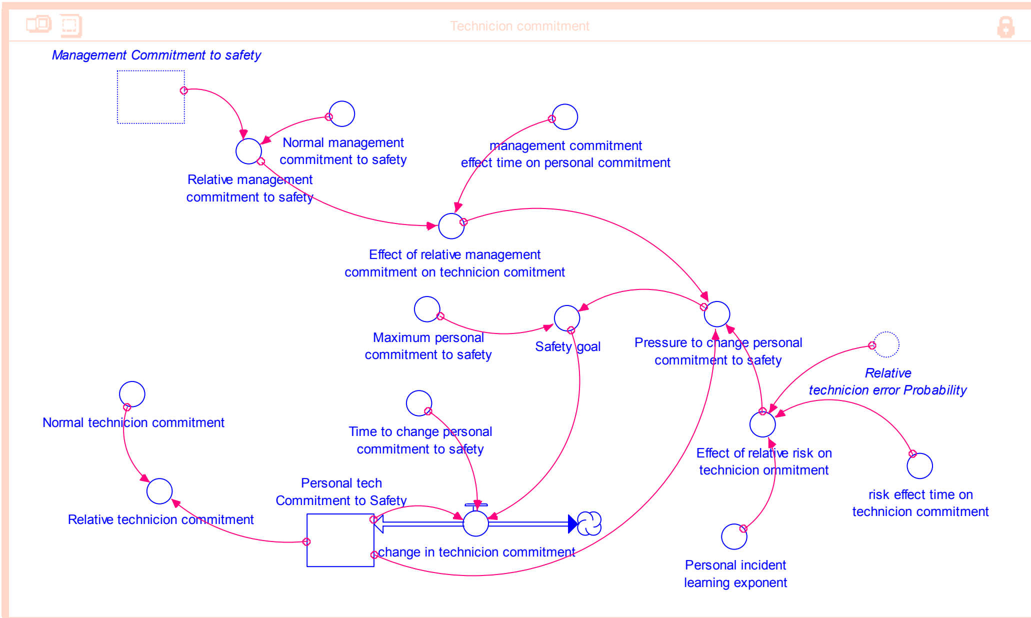

Figure 6.21 Technician's commitment module in SD environment

As Figure (6.20) shows, "relative management commitment to safety" influences technician's "personal commitment to safety". Higher management commitment to safety pressures technicians to be more committed to safety and follow the standard procedures (for maintenance). Another factor also effects technicians' level of commitment and that is the incident rates. Higher incident rates (which basically mean higher risk) will raise their commitment to safety. Obviously lower management attention to safety will eventually lead technicians to be less conscious about safety.

Similar to the "Management Commitment to Safety" module, "technician commitment to safety" has also utilized the concept of "sea anchor and adjustment" (Sterman, 2000) in modeling commitment changes. All related equations to "management commitment' module are presented in Appendix C.

The human error probability model used in "Human Reliability" module is adopted from Nuclear Action Reliability Assessment (NARA). This model uses a set of Generic Task Types (GTTs) to describe various tasks modeled in Probabilistic Risk Assessment (PRA). These GTTs are modified by considering further factors, which are known as Error Producing Conditions or Performance Shaping Factors(PSF), affecting performance. The process is mathematically simple, but needs a great deal of judgment specially when deciding which Error Producing Conditions (EPC) are present and what Assessed Proportions of 'Affect' (APOA) should be used. (B. Kirwan, et.al., 2004). Appendix C includes equations used in the "Human Reliability" module.

The output of this module, technician error probability, is fed to "management commitment" module to model the dynamics of management commitment to safety. Also, the assessed human error probability is an input to maintenance unit process model (see Section 6.3.5) in order to obtain maintenance quality index, which is the n used to calculate engine failure rate due to maintenance error.

6.3.5 Maintenance Unit Process Model & Aircraft Airworthiness in IRIS Environment

Section (6.2.4) describes the unit process model. Those factors are included in the IRIS using BBN modeling. (see Figure 6.22) The factors of this unit are affected by BBN factors of organizational safety practices (mentioned before) and regulatory auditing factors. The target node of this BBN is Aircraft Airworthiness, which is linked to engine failure model and risk scenarios using omega factor parameter (Section 6.3.6)

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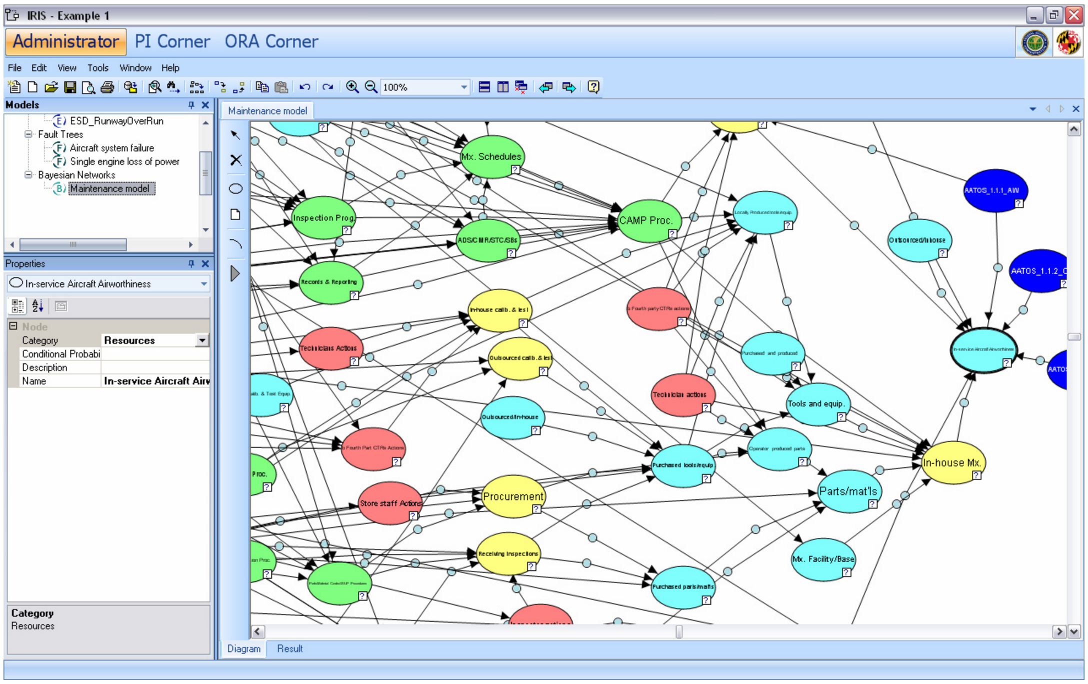

Figure 6.22 Maintenance unit process model in BBN

All the probabilities of the nodes and their related conditional probabilities are based on Eghbali's maintenance model (2006) developed for airlines.

6.3.6 Technical System Risk in IRIS Environment

In Section (6.2.1), we described the technical system risk models. In order to run this example, we select a specific scenario from Roelen(2005) for airline accident developed in IRIS. (see Figure 6.23 & 6.24) The scenario consists of two event sequence diagrams (ESD1 & ESD 28).

Aircraft system failure (ESD1) describes the accident type “uncontrolled collision with ground”. The initiating event is the aircraft system failure and it takes place in the take off phase. Single engine loss of power during landing (ESD28) describes the accident type “uncontrolled collision with ground” with single engine failure as initiating event and at landing phase.

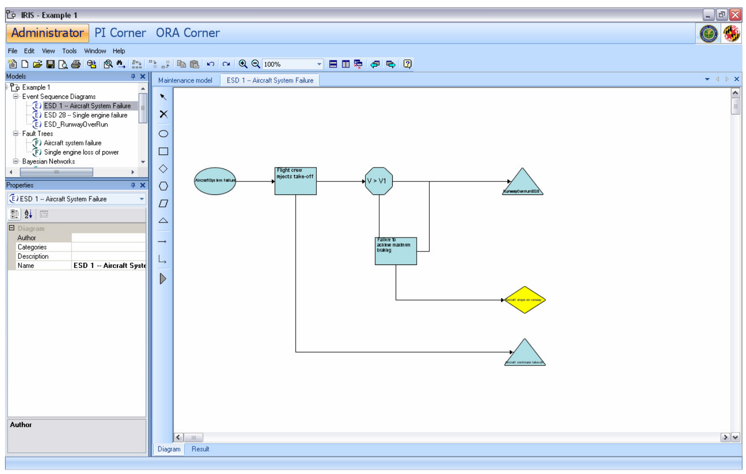

Figure 6.23 ESD 1

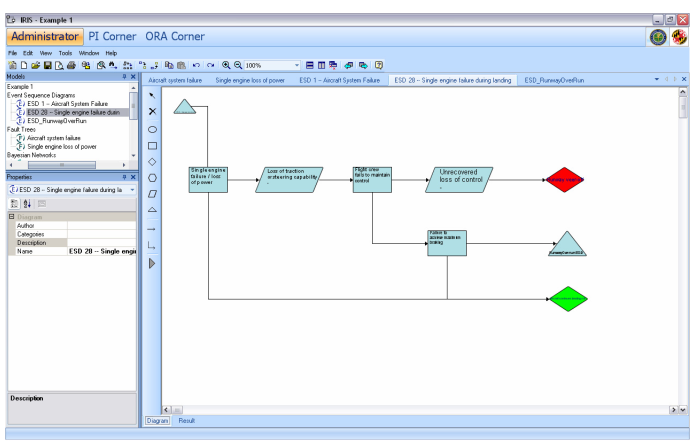

Figure 6.24 ESD 28

Both ESDs are linked to related fault trees (see Figure 6.25). Maintenance related engine failure from ESD 28 is linked to the aircraft airworthiness (BBN module described in Section 6.3.5) using the omega factor parameter, described in Section (6.2.3).

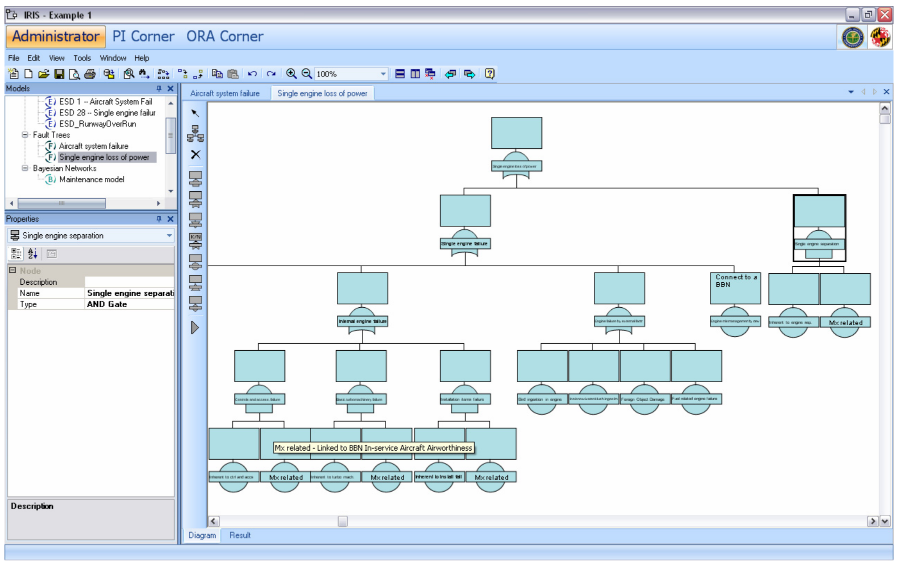

Figure 6.25 Fault tree for maintenance-related engine failure (IRIS environment)

6.3.7 Typical Outputs

a) Figure (6.26) displays the trend that could be traced in management commitment to safety, technician commitment to safety, and technician error probability in a period of 15 years. The advantage of these results over those of static models is that they are able to show the periods of increase in safety output (e.g. technician error probability in Figure (6.26)). Organization may be viewed as "safe" within a certain time period, but considerably unsafe in other periods. Modeling the dynamics of the organizations provides warnings for the potential accidents (the pick of human error in the figure).

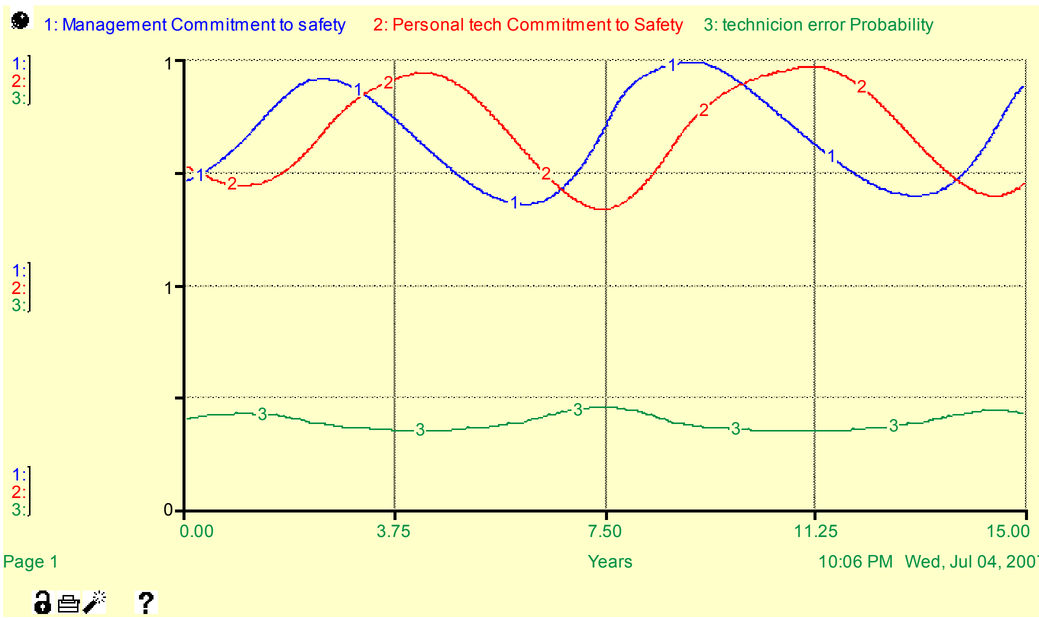

Figure 6.26 Management commitment, technician commitment, and technical probability of error in 15 years

b) Increase in human error probability leads to increase in management commitment with a time delay. This also raises technician's commitment to safety. After a while, because of the higher commitment levels of technicians, error probability starts to decline and eventually decreases management sensitivity to safety issues hence decreasing their commitment to safety, leading the rise in error probabilities.(see Figure 6.26)

c) Trend of risk over time can be seen in Figure (6.27), which shows the results over a 15 years time period. The result below indicates the period of increases in risk over the 15 years, and it emphasizes the need for dynamic organizational safety risk analysis. (referring to principle M) Since the current example, only considers the effects of organizational factors on the technicians in the maintenance module, we can not make any conclusion about the values of risk from this analysis, and only the existence of changes is highlighted. More realistic value of risk needs future research that includes the effects of organizational factors on the other elements of maintenance unit (e.g., resource and procedures) and flight crew as well.

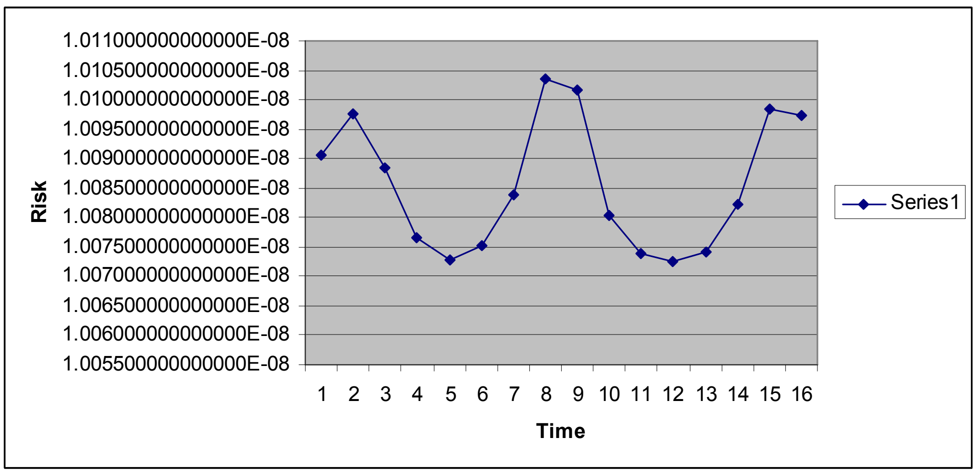

Figure 6.27 Total system risk over 15 years

d) Figure (6-28) illustrates that if for any reason (i.e. A disaster such as 911 that effects the whole industry) an airline is subjected to financial distress, management commitment to safety will decline and at the same time decrease in management commitment will cause technician error probability to incline. Observing higher error probabilities will force management to set the commitment to safety higher and meanwhile financial pressure is in effect.

The results will be a gradual increase in error probabilities and gradual decline in management commitment to safety.

Figure 6.28 Financial stress as a trigger point for gradual decline in management commitment to safety

e) Figure (6-29) displays the case, where lower error probabilities remains basically constant for the first seven years. These low error probabilities will take management concentration away from safety, suggesting that the organization is safe as is. But as the management commitment and consequently technician commitment to safety declines, error probabilities incline and, reach higher peaks later in time.

Figure 6.29 A period of low-stable human error as a trigger point for gradual decline in management commitment to safety

7. CONCLUDING REMARKS

7.1 Contributions

The results of the effort documented in this thesis can be summarized as follows:

1. A comprehensive set of "principles" upon which organizational safety theory could be built and evaluated, has been introduced. In the absence of such principles and modeling guidelines rooted in theory and empirical studies, all models look equally good, or equally poor, with very little basis to discriminate and build confidence. Therefore, this research focused on the possibility of improving the theoretical foundations and principles for the field of "*Organizational Safety Risk Analysis*". These principles are a series of testable propositions with supporting rationales, insights from other research efforts, and/or integration of different theories across diverse disciplines.
2. This research also offers a process for adapting appropriate techniques to create a "hybrid" modeling method in order to operationalize the theoretical organizational safety frameworks, in a manner consistent with the articulated principles. Ingredients are taken from techniques in Risk Assessment, Human Reliability, Social and Behavioral Science, Business Process Modeling, and Dynamic Modeling.
3. Additionally an organizational safety risk framework, named "Socio-technical Risk Analysis (SoTeRiA), has been proposed as the realization of aforementioned modeling principles. Two key characteristics of the proposed

safety risk theory are: (1) theoretically supported relations between organizational safety culture, organizational safety structure/practices, and organizational safety climate, with specific distinction made between safety culture and safety climate, and (2) the multi-level nature of the framework which explicitly recognizes the relationships among constructs at multiple levels of analysis.

4. Other contributions of this research are in implementing the proposed organizational safety framework in the aviation domain, particularly the airline maintenance system. We also applied an example of the proposed hybrid modeling environment including an integration of SD, BBN, ESD, and FT to demonstrate the feasibility and value of hybrid frameworks. This hybrid technique integrates "deterministic" and "probabilistic" modeling perspectives, and provides a flexible risk-informed decision making tool.

The US Federal Aviation Administration (FAA), which partially supported this research effort, has recognized the role of organizational factors as one of the most critical aspects in the quest to achieve 80% reduction in aviation accidents at the same time that the volume of flights is expected to increase by a factors of 2 or more. Since catastrophic accident rates are already extremely low, the identification of causal factors that could contribute to such risks and those that might help in mitigating them is very difficult. The solution requires a systematic and comprehensive methodology for causal modeling in order to relate the risk scenarios to their human and organizational performance roots, and to the regulatory and oversight function of FAA.

The challenge is that human and organization have "holistic" and "collective" natures, and predicting their performances needs modeling such holistic nature. On the other hand, we need to identify the controllable characteristics of individuals and organization in order to be able to prevent incidents and accidents. This requires a causal model that can provide specific links between such characteristics and organizational safety performance. The four contributions of this research attempt to strike a balance between these two competing needs. The foundations developed in this report form a basis for formulating the needed techniques. The resulting causal model, through proper integration with models of the technical systems, can help manage risks proactively, based on leading indicators in the safety related practices of the organization, and relevant regulatory and oversight activities.

7.2 Answers to the Open Challenges

Considerable improvements during the past two decades in the sophistication of quantitative methods of safety and risk assessment have led many to assume that the same style of causal modeling is an effective way of assessing and managing organizational safety risks. There are, however, a number of open challenges in developing a predictive model of organizational safety risk, as highlighted in Chapter (2) in details. In the path towards defining a set of "principles", developing organizational safety "theory", and implementing the "model", we have found answers for many of the open questions, addressed in Chapter (2). Our answers are at different levels: conceptual in some, specific modeling technique in others, and implementation in certain cases. The following is a summary of our answers to the specified challenges identified in Chapter (2):

Principles (C) discuss the importance of moving from models, based on "deviation from normative performance" (i.e., second-generation models) toward the models based on "actual performance" (i.e., third-generation models). We argue that the concept of "error" and "deviation" can be clearly defined for the technical system and the individuals directly operating and/or maintaining it, but this concept should not be extended to the internal factors (e.g. ,emotional and cognitive factors) and external factors (e.g. team and organizational factors) affecting the performance of individuals. The "collective" effects of organizational factors create the organizational safety performances. It is difficult to point to a single term as management or supervisor *error* that can be lined up in a chain of failures (holes in the Swiss Cheese Model (Reason, 1990)), and indeed the combined effects of different factors and "misfit" of the factors is what leads to output error of an organization. In other words, performance is a collective characteristic of an organization that emerges from the interaction of its elements.

The majority of second-generation quantitative frameworks cover three parts: organization model, operator model, and technical system model. Based on principle (D_a), the proposed safety framework in this thesis is developed as a "multi-level" theory of organizational safety performance in order to integrate macro- and micro-organizational perspectives, taking into consideration the relationships between constructs on different levels of the analysis. Thus, the proposed framework has three levels : "organization", "group", and "individual". Based on principle (D_b), for the purpose of "risk management", organizational safety framework is cross-level, covering paths of influence from organization level as a whole, to groups, and individuals, and then from the individual-level back up to organization-level safety outcome.

Technical system risk, which is the organizational-level safety outcome in the proposed theory, emerges from group and individual performance. Based on principle (L), depending on the nature of emergence, a technique should be used in order to combine the lower level constructs into the higher level construct. As we mentioned in chapter (4), technical system risk can be represented using logical techniques such as Fault Trees (FT) and Event Sequence Diagrams (ESDs). Thus, these are the candidate techniques that connect the group and individuals' performances to organizational safety outcome.

Assessing and evaluation of the third-generation technical system models is out of scope of the current thesis. Regarding the technical system, we theoretically discussed the place of technical system model in the integrated organizational framework. In the implementation part, we used second-generation models for the technical system, in order to facilitate the discussion on integrated organizational safety framework, and focus mostly on organization part.

Roelen et al. (2003) have used the concept of safety Critical Tasks (SCTs), as a link between organization and technical system scenarios. In this thesis, we borrowed this concept, and called the group or individual performances that directly affect on the elements of technical system risk scenarios as Safety Critical Tasks (SCTs). For example, maintenance performance is a safety critical task since it directly affects hardware failure (an element of risk scenarios). In general, SCTs can be either events explicitly specified (e.g. human actions) in the accident scenarios, or implicitly through model parameters (e.g. equipment failure rate). SCTs help to focus on what matters most for safety among many activities in organizations. The path of connection between group safety performances (SCTs) and organizational safety outcome covers some techniques including FT, ESD, and also Omega Factor (Mosleh & Golfeiz, 1999). The Omega factor technique is a parametric function that converts the nature of group safety performance to the nature of failure rates of the elements of risk scenarios. In this thesis, we implemented the concept of SCT and Omega factor in the aviation maintenance context.

The other possible connection in the proposed framework is the link between individual performance and group performance (i.e. SCT). As we explained in the principle (P) and also chapter (4), "process modeling technique" can model an activity (or a set of activities), and thus we use this technique to model the safety performances of the groups and make a non-linear connection between group members' performances and their output performances (SCTs). We name this linkage module "unit process model". Unit process model includes the direct activities that produce the Safety Critical Task (group safety performance). Davoudian, (1994a and 1994b) has used a similar concept (i.e. work process) in his safety framework. We generalized this concept to the multi-level framework, with separating the group level process model and the process model of supporting organizational safety practices (e.g., human-related activities, resources-related activities, and procedure-related activities). The process modeling technique is also implemented through the aviation maintenance in Chapter 6.

The proposed organizational safety framework is grounded on a "theory", rather than relying on a "set of factors" (e.g. WPAM (Davoudian et al. 1994a and 1994b)) or accident data (e.g. MACHINE (Embrey, 1992)). Based on principle (B), safety is one of the organizational outcomes/performances, thus organizational safety framework should be grounded on the organizational performance model. The theoretical frameworks for organizational effectiveness were reviewed, and the model developed by Ostroff et al. (2003) was adopted in order to create a systematic relation between safety culture, safety structure, and safety climate in a multi-level framework. The comprehensiveness (mentioned in principle G) of safety model needs the coverage and integration of the social (e.g. safety culture and safety climate) and structural (organizational safety structure & practices) aspects of organization that influence safety. Most of the previous safety models focus on either social or structural aspects. But the research that attempted to include both aspects has not established their theoretical relations. Besides, there is no clear distinction between safety culture and safety climate in the existing safety frameworks, and these two have been used, most of the time, with a verity of definitions, and interchangeably, in the frameworks.

Some of the existing second-generation safety frameworks (e.g. Embery, 1992) have mentioned human model as a link between organization and technical system risk. Modeling the third-generation human (individual) model, which is a cognitive-based model, is not the main concern of this thesis. But human model is discussed with respect to its link to the organizational factors. The term, psychological climate, is missing in the current human reliability models. We added this term as "psychological safety climate" to the individual model, as the individual's perceptions of organizational safety practices. Organizational safety structure & practices affect internal Performance Shaping Factors (PSFs) and ultimately individual safety performance through two different paths of influence: (1) Organizational safety practices collectively influence organizational safety climate, which is the shared perception of employees about actual organizational safety practices. Organizational safety climate affects *group safety climate*, which in turn influences psychological safety climate (an element of individual-level PSF). Psychological safety climate impacts individuals' motivation in the unit process model. (2) Different sub-factors in Organizational safety structure & practices can also directly impact individual internal PSFs. The direct effects are caused by the influences of "human-related activities" on the "ability" and "opportunity". For example, a low quality work environment, such as poor air conditioning and lights, can affect physical opportunity, and training has effects on people's knowledge.

The other challenge in the human and individual model is capturing the collective nature of human performance that is similar to the collectiveness in organization. In this thesis, configurational approach is proposed as a solution for dealing with dependency of individual performance shaping factors in human reliability analysis. Cluster analysis can find the specific profile or pattern across individuals' attributes. We haven't implemented this technique in this thesis.

Most of the previous studies have developed a set of organizational factors without adequate discussion about measurement approaches. Measurement approach has been studied in my research, especially for the following objectives: developing a more accurate understanding of the real state of each factor; identifying different aspects of a specific factor; understanding different paths of influences; and better treatment of the dependencies among factors. The principle (H) of the current research is proposed that the factors of the safety casual model can be measured in three different ways: objective, subjective, and combinational. Theorists need to choose the measurement method based on (1) the type, the level, and the underlying theoretical model of construct, (2) the objective accuracy, and (3) the availability of data. Besides, a Bayesian approach for combinational measurement method is proposed. Theorists should consider a Bayesian combination of two measurement approaches as an appropriate technique because of its two advantages: (1) Reducing uncertainty: this approach integrates two sources of information about the state of a factor (or an attribute), and provide more accurate estimate of the actual state of the factor (or an attribute), and (2) Possibility of combining two pieces of information with different natures including subjective and objective.

The confusion in the subject of safety measurement mainly comes from mixing the two aspects of measurement, i. e. “method” and “basis”. Measurement methods answer the question of how to measure the factors and links in the safety causal model, and measurement bases refers to which aspects of the accident causation need to be measured. The present study is an effort to clear up the confusions. Principle (K) of this thesis proposes multi-dimensional measurement perspectives that have been introduced based on measurement "methods" and different measurement "bases".

Based on principle (B), safety has interaction with other organizational performances. None of the second-generation models has considered the financial performance in their frameworks, but some of the third-generation such as Cook (2004) has considered the non-safety performance (e.g., production) in their models. In this thesis, the performance of the organization is divided into safety performance and financial performance. Safety performance impacts financial performance, and financial performance affects safety performance through a number of paths of influence. The financial performance affects the safety performance both directly and indirectly. In the current study, we use the safety culture as a barrier that eliminates the direct effects of financial pressure on the safety practices in organizations. Then, we need to substitute the statistical relation between financial pressure and safety culture. Most of the existing research has studied the effects of culture on the financial performance (e.g. Siehl and Martin, 1990), not financial performance on the culture. Besides, the investigation of the existence of a possible correlation between financial wellbeing of a firm and the safety performance of firms has been of interest to researchers and managers for a long time. This is likely of extra importance if unsafe operation could translate into a disaster. One of the challenges here is the selection of a suitable set of financial factors and correlating them to safety culture. The preferred method of studying the existence of such a correlation and the degree of its strength however is outside the scope of this thesis.

The other important aspect that is highlighted in the proposed framework is the need for dynamic modeling of organizational safety frameworks. Static organizational safety frameworks cannot capture the risk originated from: (1) delay or time-scale variations, (2) feedback loops, and (3) temporal cycles in the model. The direction and the strength of the links in organizational safety model are the function of organizational age. The time boundary and reference point of theory must be explicitly specified. The dynamic aspects of organization are discussed conceptually; a hybrid appropriate technique to capture dynamic aspects is proposed, and also implemented through the example in Chapter 6.

There is some debate about which "techniques" are more or less appropriate for organizational safety risk analysis. The candidate techniques for organizational accident causation theory are selected from risk assessment, social and behavioral science, business process modeling, and dynamic modeling techniques. As we mentioned in chapter (2) of the thesis, most of the existing second-generation safety frameworks use variations of the Bayesian Belief Network (BBN) or Influence Diagram, which is a probabilistic technique. As a first step of building the hybrid technique, we adapted BBN because of the following advantages; (1) BBN factors, with a probabilistic-based nature, can be mathematically linked to the technical system techniques (e.g., event trees and fault tress). Mosleh et al. (2005) and Wang (2007) have discussed the detail explanation about the procedure of this link, (2) there are mathematical relations between regression-based techniques and BBN. (Roehrig, 1993, Burns & Clemen, 1993) Most social and psychological theories are in form of regression-based techniques. Establishing the relation between these two techniques, we can include (quantitatively) the psychological and social theories as parts of the organizational accident causation theory, (3) BBN has a capability of applying subjective expert opinion. Adapting this technique makes the quantification of the organizational accident causation theory possible, even with a lack of actual data, (4) regression-based techniques are capable of testing causal theories using actual data. Having the relation between BBN and regression-based techniques makes the testing of the organizational accident causation theory (or at least part of that) possible, (5) for risk management purposes, it is necessary to have a technique that is capable of assessing the impacts of potential changes. BBN is a technique that can be applied for predicting the effect of changes, and (6) process modeling techniques that are appropriate for modeling unit processes and organizational practices, are semi-formal techniques, and need to be converted to formal techniques for the purpose of quantification. Since BBN is a formal technique, we proposed the conversion of process modeling technique to BBN.

On the other hand, BBN models are inadequate for representing dynamic behaviors of organization. For example, feedback loops and delay cannot be modeled properly. Therefore, the existing third-generation organizational safety frameworks mostly used System Dynamics, in order to tackle the "dynamic" mechanism of organization. Some of the third-generation frameworks (e.g. Cooke, 2004 & Leveson, 2003) have not included the existing technical system risk techniques in their frameworks. Considering that technical systems mostly lean towards "unifinality", the concept of "error" and "deviation" can be clearly defined for the technical system (referring to principle C) , and thus event chain scenarios are capable of modeling technical risks. Therefore, as a second step of building the hybrid technique, we proposed that the hybrid technique should have the capability of pre-existing classical PRA techniques (i.e., ESD, FT), which have been able to develop technical risk scenarios successfully.

We also argue that the deterministic techniques are appropriate for the case of knowing detailed information about the interrelations of the factors. But, the modelers may not have enough information about the interactions of the factors for some part of the model, and that part should be quantified using a probabilistic technique such as BBN. Thus, as a third step of building the hybrid technique, we proposed that an integration of deterministic (SD) and probabilistic (BBN) can be appropriate in that case.

For some part of the safety framework, in which the factors are highly interrelated, and modelers even have less information about the relations, a candidate technique is configurational approach. Configuration is defined as "conceptually distinct characteristics that commonly occur together" (Meyer et al., 1993, p.1175). Schulte et al. (2006, p.648) believe that configurations "allow for examining multiple characteristics simultaneously while accounting for the interrelationships and interactions among them". Configurational approach helps to capture the collective nature, without knowing the detailed relations of the factors. Therefore, configurational approach should be another possible technique in the proposed hybrid tool.

In this thesis, an example of Hybrid technique is implemented in the aviation context. The proposed methodology uses the Hybrid Causal Logic (HCL) (Mosleh, et al. 2003), with main layers of Event Sequence Diagrams (ESDs), Fault Tress (FT), and Bayesian Belief Nets (BBNs), and it integrates HCL with System Dynamics technique. ESDs on the top delineate the possible risk scenarios. The events, conditions, and causes of the scenarios are incorporated through the FTs and BBNs, i.e. the second and third layers of the HCL. SD is added to the bottom layer of the risk model to depict some deterministic and dynamic causation mechanisms. SD is a deterministic tool and its combination with BBN brings a stochastic insight of this tool to the field of organizational safety risk analysis.

7.3 Future Work

The challenge of this project has given us many new research thoughts that we mention here as a suggestion for future works:

We have already applied the proposed safety framework for an aviation maintenance system, and future work needs to extend this to the operation (e.g., flight crew), and analyze the common effects of organizational factors on operation and maintenance of an airline, and ultimately the airline risk performance. Although the main concern of this project are high risk organizations, such as nuclear power plants and airlines, and even though the risk scenarios are referring to "major" accident scenarios , the approach is general and can be applied for occupational safety as well.

Organizational structure and practices are strongly interrelated, but in this research we have not focused on the relation between safety structure (e.g. centralization, formalization) and safety practices (e.g., human resource practices, procedure-related activities). We mostly analyzed the links between organizational safety practices and safety performances. Future research needs to uncover the detailed relations between organizational safety structure and safety practices.

Layer (2-1) of the organizational safety practices, mentioned in Section (6.2.5.3), should include the related resources, procedures, and human actions for the human resource functions. We have not expanded this layer in the current work. Besides, layer (3-1) of the organizational safety practices, mentioned in the section (6.2.5.4), should include the procedure, resources, and human actions that are needed for “common activities” including design, implementation, auditing, and change system. Future work could be devoted to the development of process models for human resource practices and common activities.

As the proposed theory highlights, at the organizational level, safety culture shapes managerial decisions regarding organizational safety practices and structural features. There is some confusion about the differences between safety cultures and climate. Most surveys for safety culture include safety climate rather than safety culture. There is a need for a more comprehensive organizational safety culture survey. This can be done by adapting multiple methods, suggested by Ostrof et al. (2003) for organizational culture, including Organizational Culture Inventory (OCI) and Competing Values Framework (CVF), as well as Organizational Culture Profile (OCP).

As it is argued in the proposed framework, financial performance affects safety performance both directly and indirectly. One of the challenges here is the selection of a suitable set of financial factors and their relation with safety culture. Identification of appropriate method to study the existence of possible correlation and the degree of their strength needs future research. To our knowledge there has not been a study that carefully lookED at the interactions of these to fields in a dynamic environment.

The measurement aspect of organizational safety framework is analyzed “conceptually”, the “techniques” are also discussed, but not implemented in the current thesis. Future efforts can focus on gathering data in a longitudinal study to test the predictive power of different measurement approaches and value of the inference methods suggested in this thesis. One of the technical challenges is to account for the impact of time lags in predictions and in combining different methods of measurements.

In this thesis, we have referred to the configurational approach as an appropriate technique since it takes into consideration the simultaneous effects of social and structural elements of the safety causal model on safety performance. One important discussion about applying the configurational “fit” to safety prediction would be determining which safety causal factors to include among the many. Theoretically, incorporating more factors will make the predictions better, but at some level, it may make the model too complex to be analyzed. Future work is needed to study the configurational fit model as a predictor of safety performance and to uncover the most appropriate factors for such a study. A configurational approach was conceptually discussed in the hybrid technique, but it is not implemented in the example of Section (6.3). Future work needs to be devoted to this difficult problem.

In the example of hybrid technique in Section (6.3), we combined the second-generation technical system risk techniques with the system dynamics. The technical system method used is static. Future work can explore the use of a totally dynamic environment, third-generation technical system techniques, which also includes dynamic organizational factor model.

Reviewing the approaches in quality assessments hints an interesting direction: the idea of using quality measure as a "surrogate" of safety measure. A question is, whether we can use the concept of "Excellency" (the criteria in the European Foundation for Quality Management (EFQM) Excellence Model (Zink, 1995)) of organization as a predictor of safety performance. Future empirical studies can test and explore the existence of such a relation.

APPENDIX A: HUMAN RESOURCE FUNCTIONS

The following items are adapted from Ostroff (1995):

Selectivity in Recruiting/Hiring (SE)

- Examining various recruiting sources (e.g. want ads, employee referrals, colleges) to determine which provide the most appropriate employees
- Provide information to job applicants that realistically describes the job and company (positive as well as negative aspects)
- Regularly conduct validation studies in the tests, predictors or hiring practices used
- Use hiring procedures or tests that are based on job duties and requirements
- Use hiring procedures or tests to determine who will best fit in with the company's culture and values

Internal Staffing (ST)

- Fill non-entry level position from among present employees who desire promotion or transfers

Contingent Workforce (CW)

- Use nonpermanent workers (e.g. temps, contractors, retirees) in managerial-related jobs
- Use nonpermanent workers in professional, non-managerial jobs
- Use nonpermanent workers in low-level jobs, such as secretarial, custodial, etc.

Training and Employee Development (TR)

- Conduct formal analyses to determine the training needs throughout the company
- Develop clear specific objectives for what is to be learned in training programs
- Determine the most appropriate method (e.g., lecture, role-playing, hands-on) for teaching particular skills in training program
- Provide training (inside or outside the company) to keep employees' skills up-to-date
- Develop mechanisms to that employees are supported or rewarded for using their newly learned skills on the job
- Provide remedial or basic skills training fir those employees who need it
- Provide programs (e.g. training, mentoring, job rotation) to develop new skills and prepare employee for variety of jobs in the company
- Develop career plans and paths for employee movements in the company
- Counsel or meet with employees to discuss their own career goals and realistic career options
- Have formal orientation programs that provide new employees with information about the job

Appraisal (AP)

- Regularly (at least once a year) conduct appraisals of employees' performance
- Have supervisors/mangers meet with individual employees to give developmental performance feedback
- Develop performance appraisal forms that focus on the relevant duties and specific skills requires for successful job performance
- Train mangers in conducting accurate performance appraisals and giving employees feedback

Compensation and Reward Systems (RE)

Job Based Pay

- Determine pay levels for each job category using a formal job evolution system to compare and order jobs based on skills levels and/or experience
- Determine pay levels for each job or jobs category based on information about the "going rate" in the market
- Group jobs into pay classes or pay grades and determine a pay range for each class
- Formally analyze and determine the most appropriate mix of direct pay and benefits

Individual Merit Rewards

- Link individual employees' rewards, raised or bonuses to how well they perform the job

Contingent Rewards

- Link individual employees' rewards, raises or bonuses to how well the unit or team performs
- Regularly evaluate whether productivity goals and quality standards are being met
- Provide incentives to employees to increase productivity or quality

Organizational-Based Reward

- Use reward and compensation programs that link employees' rewards to how well the company performs (e.g. profit sharing, employee stock ownership plans)

Skill-Based Pay

- Base individual employees' raises/bonuses on a skill-based pay system

Pay Leader

- Adhere to pay policy of being a pay leader (high paying) in the industry or area

Non financial Rewards

- Encouraging managers/supervisors to use non-financial rewards such as recognition, praise, etc.

Benefit

- Provide health retirement insurance and other benefits to employees
- Have procedures to assist employees in understanding their benefits

Job Analysis (JA)

- Conduct job analyses that describe the tasks performed, behaviors, abilities, knowledge and skills needed, and equipment required to perform the job
- Update job analysis information on a regular basis

- Use standardized, systematic procedures to collect job analysis information

Job Enrichment (JE)

- Design jobs to provide employees with sufficient variety, autonomy and feedback

Team Systems (TS)

- Establish committees/teams of employees who examine productivity and quality problems and provide recommendations for changes
- Utilize autonomous workgroups or self-managed teams who have responsibilities for decisions assigning work, and determining work methods
- Use a total quality management approach to improve productivity and service

Employee Assistance (EA)

- Offer employee assistant programs to help employees deal with personal job related issues such as stress, family problems, substance abuse and financial counseling
- Sponsor or provide fitness programs for employees, such as athletic programs or fitness clubs
- Use alternative work schedule, such as flexible hours, job sharing, part time work or work at home
- Use a flexible benefits package that gives employees in allocating their benefits "dollars" across health, retirement, insurance, child care, etc.
- Provide programs or benefits to help employees balance work and family concerns such as childcare, elder care, referral networks, childcare sick leave, etc.
- Provide outplacement services, such as counseling and job search skills, for employee who are discharged or laid off

Due Process (DP)

- Have a formal grievance procedure or formal complaint resolution system for employees
- Adhere to progressive discipline system in which employees are disciplined in successive steps ranging an oral warning to eventual dismissal
- Have mechanism in place for employees to communicate suggestions or register complaints

Employee voice/Empowerment (EM)

- Have formal procedures for sharing important information with employees
- Involve employees in deigns and administration of compensation systems, performance evaluation systems, methods for enhancing productivity, etc.
- Regularly survey the opinions pf workers regarding their job conditions and satisfaction
- Involve employees in major decisions that will directly affect their work processes

Diversity (DI)

- Provide transition or other programs for employees to understand and accept members from other culture, ethnic background of gender groups
- Develop programs to increase promotion rate of members of protected classes
-

- Establish goals, time tables and/or other procedures to increase minority representation and diversity in the company
- Conduct adverse impact analyses or analyses to determine if discrimination against members of protected classes exists in hiring or promotion practices

Legal compliance (LC)

- Regularly check for compliance with laws pertaining to discriminations and disabilities
- Regularly check for compliance with laws pertaining to employee safety
- Regularly check for compliance with laws pertaining to employee rights
- Regularly check for compliance with laws pertaining to pay, compensation and benefit

Safety (SA)

- Maintain an accident record system or use committees of workers or causes of accident and safety hazards
- Train employees to emphasis safe practices in the work place
- Conduct internal safety inspection

Union Relations (UR)

- Employees unionized labor

Of those with unions:

- Monitor the number of NLRB grievances filed
- Efficiently settle collective bargaining contracts for unionized employees
- Share information with union representatives regarding the companies financial status, work conditions and potential procedural changes

APPENDIX B: SAFETY CULTURE /CLIMATE FACTORS

<u>Safety culture factors in airline maintenance (Gibbons et al., 2005)</u>

In chapter 5, we argued that these items are the mixture of safety culture and climate.

1. Organizational Commitment :

- **<u>Safety Fundamentals (SF)</u>**

  f) Shift work and day-off scheduling policies at my company greatly contribute to stress and fatigue in technicians.
  g) My company has effective shift turn- over procedures.
  h) My company's maintenance manual and information system are kept up to date.
  i) Maintenance checklists and procedures are easy to understand and use.
  j) "Return to service" aircraft documentation and record keeping is taken seriously at this company.

- **<u>Work Environment (WE)</u>**

  - Management is committed to updating tools and equipment used in aircraft maintenance (e.g. NDT equipment , diagnostic tools).
  - My company ensures that tools and equipment (e.g. work stands, hydraulic power sources , electrical equipment) are regularly inspected , serviced, and are safe to use.
  - My company ensures that the environment (e.g. lighting, air conditioning, ventilation) is conductive to effective maintenance work.
  - My company closely monitors tool control , calibration, and equipment certification.

- **<u>Safety Training (ST)</u>**

  - Maintenance technicians are given enough training to perform their work safely.
  - My company provides technicians with adequate safety related training (e.g. first aid, HAZMAT, fir).

- Training practices at my company are centered around operational and airworthiness safety

- **Safety Value (SV)**

  - Safety is defined as a “core value” in my company
  - Management is more concerned with making money than being safe.
  - People in my company would rather cancel a flight than take a chance with whether or not maintenance has been performed safely.
  - Management views regulatory violations very seriously, even when don’t result in any apparent damage.

2. Formal Safety System :

- **Reporting system (RS)**

  - Technicians don’t bother reporting mishaps or close calls since these events don’t cause any real damage.
  - The safety reporting system is convenient and easy to use.
  - Technicians can report safety discrepancies without the fear of negative repercussions.
  - Technicians are willing to report information regarding the marginal performance or unsafe actions of other technicians.
  - When technicians report a safety problem, supervisors act quickly to correct the safety issues.
  - Technicians are willing to file reports about unsafe situations, even if the situation was caused by their own actions.
  - Technicians who raise safety concerns are seen as troublemakers.

- **Response and Feedbacks (RF)**

  - When technicians report a safety problem, it is corrected in a timely manner.
  - Safety issues raised by technicians are communicated regularly to all other technicians in this airline.
  - Technicians are satisfied with the way this airline deals with safety reports.
  - My airline only keeps track of major safety problems and overlooks routine ones.

- **Safety Personnel (SF)**

  - Personnel responsible for safety hold a high status in the airline.

- Personnel responsible for safety have the power to make changes.
- Personnel responsible for safety have a clear understanding of the risks involved in flying the line.
- Safety personnel have little or no authority compared to operations personnel.
- Safety personnel demonstrate a consistent commitment to safety.

3. Informal Safety System :

- **<u>Accountability (AC)</u>**

  - Management shows favoritism to certain technicians.
  - When accident or incident happens, management always blames the technician.
  - Technicians who perform substandard work are "rewarded" by receiving only the easy jobs.
  - The process taken to investigate possible unsafe maintenance behavior is fair.
  - Standards of accountability are consistently applied to all technicians

- **<u>Professionalism (PR)</u>**

  - Technicians view the airline's safety record as their own and take pride in it.
  - Technicians who perform substandard work develop a negative reputation among other technicians.
  - Technicians with less seniority are willing to speak up regarding airworthiness safety issues.
  - Decisions made by senior technicians are difficult to challenge.
  - Technicians never cut corners or compromise safety regardless of the operational pressures to do so.

- **<u>Technicians' Authority (AU)</u>**

  - Technicians are actively involved in identifying and resolving safety concerns.
  - Supervisors support technicians who stop a job because of a concern about safety or airworthiness.
  - Technicians routinely perform operational checks after work is completed.
  - Effective communication exists up/ down the chain of command.
  - Technicians are seldom asked for input when procedures are developed or changed.

- Technicians who call in sick or fatigued are scrutinized by supervisors or other management personnel.
- Technicians have little real authority to make decisions that the safety of normal operations.

4. Supervisors : (SU)

- **<u>Supervisory Involvement</u>**

  - Supervisors distribute the workload evenly among technicians
  - Supervisors shield technicians from outside pressures(e.g. flight crews, dispatch)
  - Supervisors provide clear and helpful feedback to technicians about their safety compliance.
  - Supervisors keep technicians informed about potential hazards associated with maintenance activities.
  - Supervisors are often unhappy when technicians take time off for training.

- **<u>Marinating Standards</u>**

  - Supervisors do not permit technicians to cut corners.
  - Supervisors often fail to recognize when maintenance technicians engage in unsafe practices.
  - Maintenance supervisors closely monitor proficiency standards to ensure technicians are qualified to perform the assigned tasks.
  - Supervisors stop unsafe operations or activities .
  - Supervisors never pressure inspectors to sign-off on borderline work.
  - Supervisors are more concerned with safe maintenance that the flight schedules

APPENDIX C: MODEL EQUATIONS FOR MODLUES IN STELLA

The model is implemented in STELLA, supplied by “i see systems”. The model equations are grouped according to each module.

Hiring

Effect of relative technician commitment on quit = a graphical input

Gap in number of technicians = Target technician Demand Total technicians

Hiring time = 0.5 year

Hiring= IF Gap in Number of technicians>0 then INT ((Gap in Number of technicians*Relative management commitment to safety)/Hiring Time) ELSE 0

Rookie promotion time = 5 years

Rookie quit = INT (Rookies*Effect of Relative technician Commitment on quit*Rookie quit fraction)

Rookie quit fraction = 0.1

Senior quit = INT (Effect of Relative technician Commitment on quit*Senior quit fraction*seniors)

Senior quit fraction = 0.1

Target technician demand = Demand/Technician working hours per year

Technician working hours per year = 2000 hrs/year

Total technicians = rookies + seniors

Up to speed = Rookies/Rookie promotion time

Training

Average experience of technicians hired = 1000 hours

Average technicians experience = Total technicians Experience/Total technicians

Experience gap = Max (Target experience Average technicians experience,0)

Increase in experience from hiring = Hiring*Average experience of technicians hired

Increase on job experience = Total technicians*Safety experience gained in flights*Training

Loss of experience from attrition = Total Number of Quits*Average technicians experience

Reference Experience = 5000 hours

Relative experience of technicians = Average technicians experience/Reference experience

Safety experience gained on job = Relative technician commitment

Target experience = 2000 hours

Time to provide training = 0.5 year

Total number of quits = Rookie quit + Senior quit

Training = (Experience gap*Relative management commitment to safety)/Time to provide training

Management Commitment to Safety

Change in management commitment to safety = (Target management commitment to safety Management Commitment to safety)/Time to change management commitment to safety

Effect of financial pressure on management commitment to safety = SMTH1 ((Management drive to prioritize financial situation over safety) ^FP exponent, FP effect time)

Effect of relative technician error on management commitment to safety = SMTH1 ((Relative technician error Probability) ^exponent, effect time)

FP effect time = 0.25 year

FP exponent = 0.1

Management drive to prioritize financial situation over safety = if Z score<2 then Z score else Z score*0.3

Pressure to change management commitment to safety = MAX (0.020, Management Commitment to safety)*Effect of relative tech error on management commitment to safety*Effect of financial pressure on management commitment to safety

Reference technician error = 0.2

Relative technician error probability = technician error Probability/reference technician error

Safety pressure effect time = 0.25 year

Safety pressure exponent = 0.8

Target management commitment to safety = min (Pressure to change management commitment to safety, 1)

Time to change management commitment to safety = 0.5 year

Technician Commitment to Safety

Change in technician commitment = (Safety goal - Personal tech Commitment to Safety)/Time to change personal commitment to safety

Effect of relative management commitment on technician commitment = SMTH1 ((Relative management commitment to safety), management commitment effect time on personal commitment)

Effect of relative risk on technician commitment = SMTH1 ((Relative technician error Probability) ^Personal incident learning exponent, risk effect time on technician commitment)

Management commitment effect time on technician commitment to safety = 0.25 year

Maximum personal commitment to safety = 1

Normal management commitment to safety = 0.8

Normal technician commitment to safety = 0.8

Personal incident learning exponent = 0.4

Pressure to change personal commitment to safety = MAX (Personal tech Commitment to Safety, 0.020)*Effect of relative management commitment on technician commitment*Effect of relative risk on technician commitment

Relative management commitment to safety = Management Commitment to safety/Normal management commitment to safety

Relative technician commitment = Personal tech Commitment to Safety/Normal technician commitment

Risk effect time on technician commitment = 1 year

Safety goal = min (Maximum personal commitment to safety, Pressure to change personal commitment to safety)

Time to change personal commitment to safety = 0.25 year

Human Reliability

APOA experience = graphical function

APOA moral = graphical function

APOA time pressure = graphical function

Demand =280000 hours

EPC experience = 8

EPC moral = 2

EPC time pressure = 11

GTT = 0.01

Regulatory allowed working hours = 2000 hours/year

Technician error probability = GTT*(((EPC time pressure-1)*APOA time pressure+1)*((EPC experience-1)*APOA experience+1)*((EPC moral-1)*APOA moral+1))

Technician error probability input to IRIS= technician error Probability / 10

Time available = Total technicians*Regulatory allowed working hours

Time Pressure = demand / Time available

financial Pressure

Decrease = if Relative risk>1 then Z score* Z decreasing multiplier else 0

Decrease in Z = Delay ((smth1 (Decrease, .01)), 0.1)

Decreasing multiplier = 0.05

Increase = if Relative risk <1 then Z score*Z increasing multiplier else 0

Increase in Z = Delay ((SMTH1 (Increase, 0.01)), 0.1)

Relative risk = Relative technician error Probability

Z increasing multiplier = 0.05

APPENDIX D: TECHNICAL SYSTEM RISK ANALYSIS TECHNIQUES

In order to describe the essence and role of *ESDs*, we refer to Figure (0.1).

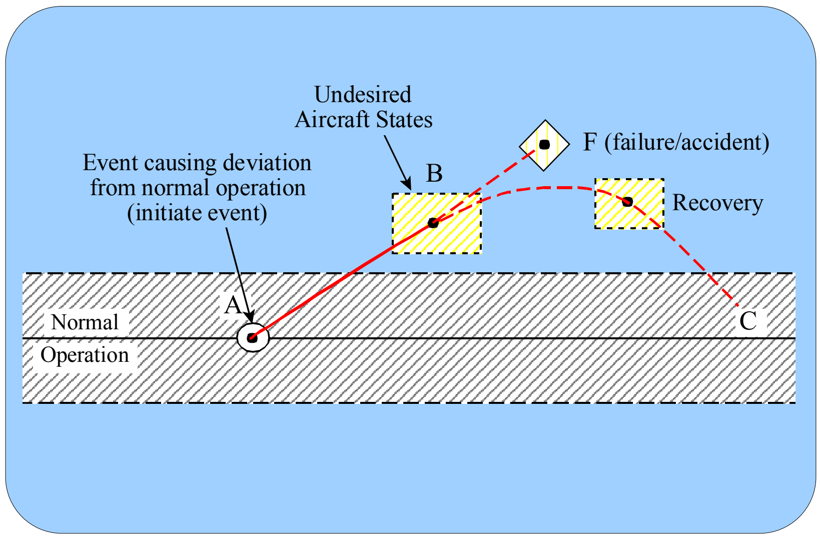

Figure 0.1 Accident Scenario Context for Safety Analysis (NASA PRA Procedures Guide, Stamatelatos, 2002)

The figure depicts the change of state of a technical system initially operating within the "safe functional/physical zone" (shaded area). At point "A" an event (e.g., equipment failure) occurs, causing deviation from the safe zone, putting the technical system in an undesired state (point "B"). Another event (e.g., crew recovery action) is initiated at that point, and depending on whether it succeeds or fails, the technical system is put back into the safe zone (point "C"), or otherwise an accident occurs (point "F"). The sequence of events from A (the initiating event) to the end states (C or F) forms two simple *scenarios*. These scenarios provide the context within which the events and their causes are evaluated as potential hazards or sources of risk. An

ESD is a visual representation of a set of possible risk scenarios resulting from an initiating event. Historically, "*Event Sequence Diagram*" has been a loosely defined term, and *ESDs* have been used in a variety of industries for different purposes. They have been used in probabilistic risk analyses by the nuclear power and aerospace industries to develop and document the basis for risk scenarios, and also to communicate risk assessment results and models to designers, operators, analysts, and regulators. *ESDs* have also been used in the aviation industry as part of safety and reliability analysis of aircraft systems. NASA has used *ESDs* to help identify accident scenarios. In all three applications mentioned above, *ESDs* have been used both qualitatively for the identification of hazards and risk scenarios, as well as quantitatively to find probabilities of risk scenarios (Stamatelatos, et. al, 2001).

Other methods, closely related to ESDs and used in risk and safety analysis of complex systems, are *Event Trees* and *Decision Trees*. Both are inductive logic methods for identifying the various possible outcomes of a given initiating event, but differ in how they are applied, depending upon whether human control can influence the outcomes (as in decision trees) or whether the outcomes depend only upon the laws of science (as in event trees). The "initiating event" in a decision tree is typically a particular business or risk acceptance decision, and the various outcomes depend upon subsequent decisions. In risk analysis applications, the initiating event of an event tree is typically a component or subsystem failure, and the subsequent events are determined by the system characteristics. As in ESDs, an event tree begins with a defined accident-initiating event. This event could arise from the failure of a system component, or it could be initiated externally to the system. Different event trees must be constructed and evaluated to analyze a set of accidents. Once an initiating event is defined, all of the safety systems that can be utilized after the accident initiation must be defined and identified. These safety systems are then structured in the form of headings for the event tree. This is illustrated in Figure (0.2) for two safety systems that can be involved after the defined initiating event has occurred.

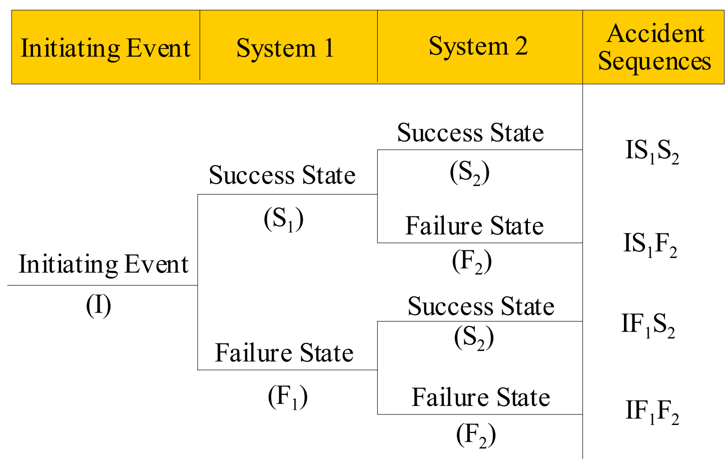

Figure 0.2 Illustration of an Event Tree

Once the systems for a given initiating event have been identified, the set of possible failure and success states for each system must be defined and enumerated. Careful effort is required in defining success and failure states for the systems to ensure that potential failure states are not included in the success definitions; much of this analysis is done with the fault tree technique discussed earlier. If bifurcation (two-state) modeling is employed, for example, then one failed state and one success state are defined for each system, and each gives a branch of the tree; if a greater number of discrete states is defined for each system (such as would be used when including partial failures), then a branch must be included for each state.

Once the system failure and success states have been properly defined, the states are then combined through the decision-tree branching logic to obtain the various accident sequences that are associated with the given initiating event. As illustrated in figure (4.2), the initiating event is depicted by the initial horizontal line, and the system states are then connected in a stepwise, branching fashion; system success and failure states have been denoted by S and F, respectively.

FTs(Figure 0.3) have been extended to include various types of logic relations - Priority AND gates, Sequence Dependency gates, Exclusive OR gates, and Inhibitor gates (Dugan et al. 1990) and have been extended to include multi-state systems (Veeraraghavan & Trivedi, 1994, Wood 1985, Yu et al. 1994, and Zang et al.2003).

To conduct the construction of a *fault tree* for a complicated system, it is necessary to first understand how the system functions. A system function diagram (or flow diagram) is used to initially depict the pathways by which signals or materials are transmitted between components comprising the system. A second diagram, a functional logic diagram, is sometimes needed to depict the logical relationships of the components.

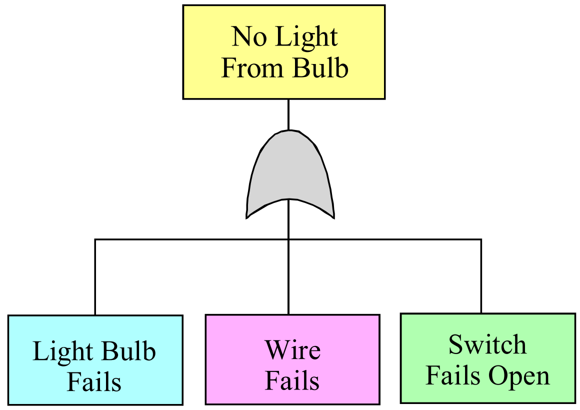

Figure 0.3 Example of a Fault Tree Logic Diagram

APPENDIX E: BAYESIAN BELIEF NETWORK (BBN)

Bayes' theorem in the subjective theory of probability is at the core of the inference engine of BBNs. Bayes' theorem was formulated by Rev. Thomas Bayes in 1763 (published in the Philosophical Transaction of the Royal Society of London) and is based on the conditional probability decomposition of the joint probability of events. Accordingly, for two events A and B we have:

$$\Pr(A \mid B) = \frac{\Pr(B \mid A)\Pr(A)}{\Pr(B)} \qquad \text{(Equation E.1)}$$

where:

Pr(A | B): Posterior, updated probability of A in light of new evidence or condition B,

Pr(A): Prior probability of A,

Pr(B | A): Likelihood of observing evidence B, given the occurrence of A.

The theorem states that starting with a prior probability, upon availability of new information, one's state of knowledge about the occurrence of an event is updated according to Bayes' formula.

Bayesian Networks can be viewed as a representation of the joint probability distribution, or as an encoding of a collection of conditional independence statements. The two views are equivalent, but the first one turns out to be more helpful in understanding how to construct networks, whereas the second one is helpful in designing inference procedures.

In *BBNs*, every entry in the full joint probability distribution can be calculated from the information in the network. A generic entry in the joint distribution is the probability of a conjunction of particular assignments to each variable, such as $\Pr(X_1 = x_1 \cdots X_n = x_n)$ which is denoted as $\Pr(x_1, ..., x_n)$. Then the joint probability is the product of all appropriate conditional probability tables in the Bayesian Networks. The conditional probability table provides a decomposed representation of the joint distribution.

$$\Pr(x_1, \ldots, x_n) = \prod_{i=1}^{n} \Pr\left[x_i \mid \text{parents}(X_i)\right] \qquad \text{(Equation E.2)}$$

where parents(X_i) denotes the specific values of the variables in Parents(X_i).

BBN have been widely used in intelligent decision aids, data fusion, intelligent diagnostic aids, automated free text understanding, and data mining. The application of *Bayesian Belief Networks (BBNs)* has also recently received increased attention in the field of reliability engineering and risk assessment. *BBNs* are applied to increase the flexibility of the modeling environment, as well as opening the way to new applications such as fault finding.

It may be evident that a Bayesian Network can be viewed as a probabilistic "expert system" in which the probabilistic knowledge base is represented by the topology of the network and the conditional probability tables of each node.

LIST OF REFERENCES

1. Agyris , C., & Schon, D., 1996, *Organizational Learning II: Theory, Method and Practice,* Reading, MA: Addison-Wesley

2. Akers, S. B., 1978, "Binary Decision Diagrams", *IEEE Trans. Computer*, C-276 (Aug.), pp. 509-516

3. Altman, E., 1968, "Financial Ratios, Discriminant Analysis and the Prediction of Corporate Bankruptcy," *Journal of Finance,* Vol. XXIII, No.4, pp.589-609

4. Ancona, D., & Chong , C.,1997, Entertainment: Pace, cycle, and rhythm in organizational behavior. In L.L. Cummings & B. Staw (Eds.) , *Research in organizational behavior*, Vol. 18, pp.251-284, Greenwich, CT:JAI Press

5. Anderson, R., Lenz, R., 2001, “Modeling the Impact of Organizational Change: A Bayesian Network Approach”, *Organizational Research Method*, Vol.4, No. 2, pp.112-130

6. Aronoff, J. & Wilson, J.P., 1985, *Personality in the social process*. Hillsdale, NJ : Lawrence Elbraum

7. Aycan, Z., Kanungo, R.N., & Sinha, J.B.P., 1999, Organizational culture and human resource management practices: The model of culture fit. *Journal of Cross-Cultural Psychology*, Vol. 30, pp.501-526

8. Bacharach, S., 1989, “Organizational Theories: Some Criteria for Evaluation”, *Academy of Management Review*, Vol.14, pp.496-515

9. Baines, T.S., Asch, R., Hadfield, L., Mason, J.P., Fletcher, S., & Kay, J.M., 2005, “Towards a theoretical framework for human performance modeling within manufacturing systems design”, *Simulation Modeling Practice and Theory*, Vol. 13, pp. 486-504

10. Baron, M., Pate-Cornel, E., 1999 “Designing Risk-Management Strategies for Critical Engineering Systems”, *IEEE Transactions on Engineering Management*, V. 46, No.1, pp. 87-100

11. Barriere, M., D. Bley, S. Cooper, J. Forester, A. Kolaczkowski, W. Luckas, G. Parry, A. Ramey-Smith, C. Thompson, D. Whitehead, & J. Wreathall, 2000, “Technical Basis and Implementation Guideline for A Technique for Human Event Analysis (ATHEANA)”, NUREG-1624, Rev. 1, Washington D.C.: U.S. Nuclear Regulatory Commission

12. Barry Gerhart, 2007, "Horizontal and Vertical Fit in Human Resource Systems", in Ostroff, C. & Judge, T. (Eds.), *Perspectives on Organizational Fit,* Lawrence Erlbaum Associates

13. Bella, 1997, "Organized Complexity in Human Affairs The Tobacco Industry", *Journal of Business Ethics,* Vol. 16, pp. 977-999

14. Benner, L., 1975, "Accident theory and accident investigation." In: *Proceeding of the Annual Seminar*, pp. 148-154. Society of Air Safety Investigation , Ottawa

15. Bier, V.M., 1999, "Challenges to the Acceptance of Probabilistic Risk Analysis," *Risk Analysis* 19, 4, 703-710

16. Biondi , E.L., 1998, *Organizational factors in the reliability assessment of offshore systems*, Master thesis of Ocean Engineering, , Oregon State University, Corvallis, Ore.

17. Bliese, P.D., 2000, Within-group agreement, non-independence, and reliability: implications for data aggregation and analysis. In K. J. Klein & S.W.J. Kozlowski (Eds.). *Multilevel theory, research and methods in organizations* , pp. 512-556, San Francisco; Jossey-Bass

18. Bobbio, A., Portinale, L., Minichino, M., Ciancamerla, E., 1999, "Comparing Fault Trees and Bayesian Networks for Dependability Analysis", *Proceedings of the 18th International Conference on Computer Safety, Reliability and Security*, SAFECOMP99, Vol. 1698, pp. 310–22

19. Bollen, K., 1989, *Structural Equations With Latent Variables* , John Wiley & Sons

20. Bryant, R.,1987, "Graph Based Algorithms for Boolean Function Manipulation", *IEEE Transactions on Computers,* Vol. 35, No. 8, pp. 677-91

21. Burke, W., & Litwin, G. "A Causal Model if organizational Performance and Change", *Journal of Management*, 1992. Vol. 18, No. 3, pp. 523-545

22. Carley, K., 2000, "Organizational adaptation in volatile environments", in *Computational modeling of behavior in organizations*, American Psychology Association

23. Carley , K., & Lin,Z. , 1997, "A theoretical study of organizational performance under information distortion" ,*Management science*, Vol. 43, pp. 976-997

24. Carroll, J, Rudolph, J., & Hatakenaka, S., 2002, " learning From Experience in High-hazard Organizations", In Staw, B., Kramer, R. (Ed.) *Research in Organizational Behavior- An Annual Essay and Critical Reviews*, Vol. 24, pp. 87-137

25. Carson, J., 2002, "Model Verification and Validation", *Proceedings of the 2002 Winter Simulation Conference,* pp.52-58

26. Cheyne, A.Cox, S., Oliver, A., & Tomas, J.M., 1998, "Modeling safety climate in the prediction of levels of safety activity". *Work and Stress*, Vol. 12, pp. 255-271

27. Cooke, D.L., 2004, *The Dynamics and Control of Operational Risk*, Ph.D Thesis , The university of Calgary

28. Cooper, M.D.,2000, "Towards a model of safety culture", *Safety Science*, 36, pp.111-136

29. Cox, S., & Cox, T., 1991, "The structure of employee attitudes to safety: A European example", *Work & Stress*, Vol. 5. pp. 93-104

30. Cox, S., & Flin, R., 1998, "Safety culture: Philosopher's stone or man of straw?", *Work & Stress*, Vol. 12, No. 3 , pp.189-201

31. Davoudian, K., et.al., 1994a, "Incorporating Organizational Factors into, Risk Assessment through the analysis of Work Processes", *Reliability Engineering and System Safety*, Vol. 45, pp.85

32. Davoudian, K., et. al., 1994b, "The Work Analysis Model (WPAM)", *Reliability Engineering and System Safety*, Vol. 45, pp.107

33. Gordon , R.P.E. , 1998, "The contribution of Human Factors to accidents in the Offshore Oil Industry" , *Reliability Engineering and System Safety*, Vol. 61, pp. 95-108

34. Deal, T.E., & Kennedy, A.A., 1982, *Corporate Cultures: The Rites and Rituals of Corporate Life. Reading*, MA: Addison-Wesley

35. Degani A. & Wiener E., 1994, "Philosophy, policies, procedures and practices: The four "Ps" of flight deck operations", in N. Johnston , N. MacDonald and R. Fuller (Eds.) , *Aviation Psychology in Practice* , Aldershot : Svebury

36. Delery, J.E., & Doty, D.H., 1996, "Modes of theorizing in strategic human resource management: tests of universalistic, contingency, and configurational performance predictions", *Academy of Management Journal*, Vol. 39, pp. 802-835

37. Delisi, P.S., 1990, “Lessons from the stell axe: Culture, technology, and organizational change”, *Sloan Management Review*, Vol. 32, pp. 83-93

38. Diergardt, M. , 2005, *Modeling Scenarios for Analyzing the Risk of Complex Computer Based Information System*, Ph.D Thesis , Swiss Federal Institute of Technology Zurich

39. DoD (Department of Defense), 1980, *Procedures for performing a failure mode, effects and criticality analysis*, Washington, DC

40. Dubin, R., 1978, *Theory development* , New York; Free Press

41. Dugan, J.B., S. J. Bavusoand, M. A. Boyd, 1990, "Fault Trees and Sequence Dependencies", *Proc. Reliability and Maintainability Symp.*, pp. 286-293

42. Edwards, D., 1986, *Out of Crisis*, Cambridge, MA ; Center for Advanced Engineering Study, Massachusetts Institute of Technology

43. Eghbali, H & Mandalapu S. 14 CFR Part 121: Air Carriers’ Maintenance Operations Causal Model. Federal Aviation Administration, 2005

44. Eghbali, H., 2006, “Performance Measures and Risk Indicators for Title 14 CFR Part 121 Air Carriers’ Maintenance Operations”, U.S. Department of Transportation, Federal Aviation Administration, William J. Hughes Technical Center, Flight Safety Branch

45. Embrey, D.E. , 1992, “Incorporating management and organizational factors into probabilistic safety assessment”, *Reliability Engineering and Systems Safety*, Vol. 38, pp.199-208

46. Embrey, D.E., Humphreys, P., Rosa E.A., Kirwan, B., & Rea, K., 1984, *SLIM-MAUD: An approach to assessing human error probabilities using structured expert judgment*, NUREG/CR-3518, Washington, D.C.: Nuclear Regulatory Commission.

47. Emry, F.E., & Trist, E.L. , 1960, ”Socio-technical systems”, In *Management Science Models and Techniques* , Vol.2, London: Pergamon

48. Fahlbruch, B., Wilpert, B., & Vincent, C., 2000, “Approaches to Safety” , in C. Vincent and B. Mol (eds.), *Safety in Medicine* (Pergamon)

49. Federal Aviation Administration Report, 2001, “Air CARRIER Operation System Model, DOT/FAA/AR-0045

50. Fleishman, E.A., & Zaccaro, S.J., 1992, "Toward a taxonomy of team performance functions". In R.W. Swezey & E.Salas (Eds.), *Teams: Their training and performance* , pp.31-56, Norwood, NJ: Ablex

51. Flin, R., Mearns, K., Gordon, R., & Fleming, M.T., 1998, "Measuring safety climate on UK offshore oil and gas installations", Safety *and Environment in Oil and Gas Exploration and Productio*. SPE International Conference in Health, Caracas, Venezuela

52. Flin, R., Mearns, K., O'Connor, P., & Brydon, R. , 2000, "Measuring safety climate : identifying the common features", *Safety Science*, Vol. 34, pp.177-192

53. Fogarty, G., 2004, "The role of organizational and individual differences variables in aircraft maintenance performance", *International Journal of Applied Aviation Studies*, Vol. 4, No. 3, pp.73-90

54. Ford, A.,1999, *Modeling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems*, Washington, D.C.: Island Press

55. Forrester, J., 1961, *Industrial Dynamics*, Cambridge, Massachusetts: The MIT Press

56. Galvin , J., 2002, *Air Traffic Resource Management Strategies and the Small Aircraft Transportation System: A system Dynamics Perspective*, Ph.D thesis, Virginia Polytechnic Institute and State University

57. Ghanadesikan, R., Blashfield, R.K., Breiman, L., Dunn, O.J., Friedman, J.H., Fu, K.,Hartigan, J.A., Kettenring, J.R., Lachenbruch, P.A., Olshen, R.A., & Rohlf, F.J., 1989, "Deterministic analysis and clustering", *Statistical Science*, Vol. 4, pp.34-69

58. Gibbons, A.M., Thaden, T., and Wiegmann, D., 2005, "Development of a Commercial Aviation Safety Culture Survey for Maintenance Operation", *Technical Report AHFD-05-06/ FAA-05-02*

59. Good, W., 1999, *Intellectual Capital and Wealth Creation: A case Study of Total Quality Management at a Large Cargo Aircraft Operator*, Ph. D thesis, Colorado Technical University

60. Gordon , R.P.E. , 1998, "The contribution of Human Factors to accidents in the Offshore Oil Industry" , *Reliability Engineering and System Safety* , Vol. 61, pp. 95-108

61. Groen, F., C. Smidts, A. Mosleh, & Swaminathan, S., 2002, "QRAS – The Quantitative Risk Assessment System", IEEE 2002 Proceedings Annual RELIABILITY and MAINTAINABILITY Symposium, pp. 349-358

62. Groenewg, J., 1992, *Controlling the Controllable: The management of safety*, Leiden. DSWO Press, Leidin University

63. Hafmann, D., Stezer, A., 1996, "A Cross Level Investigation of Factors Influencing Unsafe Behavior and Accidents", *Personal Psychology*, Vol. 49, pp. 301-339

64. Hale, A. R. and M. Hale, 1972, *A Review of the Individual Accident Research Literature*, HMSO, London.

65. Hale, A. R., B.H.J. Heming, J. Carthey and Kirwan , 1997, "Modeling of safety management system" , *Safety Science*, Vol. 26, pp. 121-140

66. Hale, A., Baram, M., 1998, *Safety Management* , Elsevier Science

67. Hannon, B. and M. Ruth, 2001, *Dynamic Modeling* 2ed, Springer

68. Heins, W., 1993, *Structured Analysis and Design Technique (SADT) :Application on Safety Systems,* TopTech Studies , Delft

69. Henley, E., & Kumamoto, H., 1981, *Reliability Engineering and Risk Assessment*, Englewood Cliffs, NJ, Prentice-Hall

70. Hofstede, G., Neuijen, B., Ohayv, D. D., & Sanders, G., 1990, "Measuring organizational culture: A qualitative and quantitative study across twenty cases", Administrative *Science Quarterly*, Vol. 35, pp. 286-316

71. Hollnagel, E., 1998, *Cognitive Reliability and Error Analysis Method (CREAM)* , Elsevier

72. Hu, Y. , 2005 , *A Guided Simulation Methodology for Dynamic Probabilistic Risk Assessment of Complex Systems*, Ph.D thesis, University of Maryland, Center for Risk and Reliability

73. Hudson, P., 2002, *Aviation Safety Culture* , Center for Safety Science, Leiden University

74. Ichniowski, B., & Shaw, K., 1999, "The effects of human resource management systems on economic performance: An international comparison of US and Japanese plants", *Management Science*, Vol.45, No. 5, pp.704-721

75. Jackofsky, E.F., & Slocum, J.W., Jr. , 1988, "A longitudinal study of climates", *Journal of Organizational Behavior*, Vol. 8, pp. 319-334

76. Jacobs, R., Haber, S., " Organizational processes and nuclear power plant safety", Reliability Engineering & System Safety, Volume 45, Issues 1-2, 1994, Pages 75-83

77. James, L.R., 1982, "Aggregation bias in estimate of perceptual agreement", *Journal of Applied Psychology*, Vol. 67, pp. 219-229

78. James, L.R., Jones, A.P. ,1974, "Organizational climate: A review of theory and research", *Psychological Bulletin* , Vol. 81, pp.1096-1112

79. James, L.R., Mulaik, S., & Brett, J., 1982, *Causal analysis: Assumptions, models, and data*, Beverly Hills, CA: Sage.

80. Jensen, F.V., Lauritzen, S., & Olesen, K.G., 1990, "Bayesian Updating In Causal Probabilistic Networks by Local Computation", *Computational Statistics Quarterly* , Vol. 4, pp. 269-282

81. Johnson, J.J., & McIntye, C.L., 1998, "Organizational culture and climate correlates of job satisfaction", *Psychological Reports*, Vol. 82, pp. 843-850

82. Johnson, W.G., 1980, *The Management Oversight and Risk Tree* (MORT) *Safety Assurance Systems,* National Safety Council, Marcel Dekker

83. Katz, D., & Kahn, R.L., 1978, *The Social psychology of Organizations* (2nd Ed.) New York: Wiley

84. Kennedy, R., Kirwan, B.,1998, "Development of hazard and operability-based method for identifying safety management vulnerabilities in high risk system", *Safety Science,* Vol. 30, pp. 249-274

85. Kim, M.C., and P. H. Seong, 2002, "Reliability Graph with General Gates: An Intuitive and Practical Method for System Reliability Analysis", *Reliability Engineering and System Safety,* Vol. 78, No. 3, pp. 239-246

86. Kirwan, B., Gibson, H., Kennedy, R., Edmunds, J., Cooksley, G., & Umbers, I., 2004, "Nuclear Action Reliability Assessment (NARA): A Data-Based HRA Tool", *The 7th Probabilistic Safety Assessment and Management*, Berlin, Germany: Springer

87. Klein, K.J., Dansereau, F., & Hall, R.J., 1994, "Levels issues in theory development, data collection, and analysis", *Academy of Management review*, Vol. 19, pp. 195-229

88. Kopelman, R.E., Brief, A.P., 1990, "The role of climate and culture in productivity". In B. Schnieder (Ed.), *Organizational climate and culture* pp.282-318, San Francisco; Jossey-Bass

89. Kozlowski, & Doherty, M.L., 1989, "Integration of climate and leadership; Examination of a neglected issue", *Journal of Applied Psychology*, Vol. 74, pp. 721-742

90. Kozlowski, S., Gully, S.M., Nason, E.R., & Smith, E.M., 1999, "Developing adaptive teams: A theory of compilation and performance across levels and time", In D.R. Ilgen & E.D. Pulakos (Eds.), *The changing nature of work performance: Implication for staffing personnel actions*, and development. San Francisco : Jossey-Bass

91. Kozlowski, S., & Hults, B.M., 1987, "An explanation of climates for technical updating and performance", *Personnel Psychology*, Vol.40 , pp. 539-563

92. Kozlowski, S., Klein, K., 2000, "A Multilevel Approach to Theory and Research in Organizations; Contextual, Temporal, and Emergent processes", in Katherine J. Klein & Steve.W.J. Kozlowski, (Eds) *Multilevel Theory, Research, and Methods in Organizations: foundations, extensions, and new directions*, Jossey-Bass Inc.

93. Kozlowski, & Salas, E., 1997, "An organizational systems approach for the implementation and transfer of training", In J.K. Ford, S.W.J. Kozlowski, K.Kraiger, E. Salas, & M. Teachout (Eds.), *Improving training effectiveness in work organizations* , pp.247-287, Mahawash, NJ: Erlbaum

94. Lee, C.Y., 1959, "Representation of Switching Circuits by Binary-Decision Programs", *Bell system Tech J.* , Vol. 38, No. 4, pp. 985-999

95. Leveson, N. , 2004 , "A new accident model for engineering safer systems", *Safety Science*, Vol. 42, No. 4, pp.237-270

96. Lewin, K., 1951, *Field Theory in Social Science,* New York :Harper and Row

97. Lin, C., Madu, C.N., & Kuei , C.H.,1999, "The association between organizational climate and quality management practices : An empirical study on small- and medium-sized manufacturing companies in Taiwan", *Total Quality Management*, Vol. 10, pp. 863-868

98. Llory, M., 1992, "Human reliability and human factors in complex organizations: epistemological and critical analysis--Practical avenues to action", *Reliability Engineering & System Safety*, Vol. 38, pp.109-117

99. Luxhoj, J., 2004, “ Building a safety Risk Management system: A proof-of-concept prototype”, *FAA/NASA Risk Analysis Workshop*

100. Marca, D.A. & MacGowan, C.L. , 1988, SADT; *Structured Analysis and Design Technique*, McGraw-Hill, NewYork

101. Mayer, R.J., Menzel, C.P., Paineter, M.K., de Witte, P.S., Blinn, T., & Perakath, B., 1995, “Information integration for concurrent engineering (iice) idef3 process description capture method report”, *Technical report, Knowledge BASED Systems, Inc.*, College Station , TX

102. McCabe, R., 1998, *Why Airline Succeed or Fail: A System Dynamics Synthesis*, Ph.D thesis , The Claremont Graduate University

103. Mearns, K. , Whitaker, S., Flin, R., 2003, “Safety Climate , Safety Management Practice and Safety Performance in Offshore Environments”, *Safety Science*, pp. 641-680

104. Meyer, A.D., Tsui, A.S., Hinings, C., 1993, “Configurational approaches to organizational analysis”, *Academy of Management Journal*, Vol. 36, pp. 1175-1195

105. Mintzberg, H.T., 1983, *Structure in fives: Designing effective organizations*, Englewood Cliffs, NJ: Prentice-Hall

106. Modarres, M., 2006, *Risk Analysis in Engineering; Techniques, Tools, and Trends*, Taylor & Francis Group

107. Mohagheh, Z., Kazemi, R., and Mosleh, A., 2006, “Incorporating Organizational Dynamic behavior into System Risk Model”, Presented at Society for Risk Analysis Annual Meeting

108. Mosleh, A. & Apostolakis, G., 1984, "Models for the Use of Expert Opinions," in Low Probability, High Consequence Risk Analysis: Issues, Methods and Case Studies, R.A. Waller, and V.T. Covello, (Eds.) Plenum Press, New York

109. Mosleh, A., Chang, Y., 2004a, “Human Reliability course, lecture notes”

110. Mosleh ,A., Chang, Y. H, 2004b, “ Model-based human reliability analysis: prospects and requirements”, *Reliability Engineering & System Safety*, Vol. 83, Issue 2, pp.241-253

111. Mosleh, A. Dias, G. Eghbali, K. Fazen , 2004, “An integrated framework for identification, classification, and assessment of aviation systems hazard”,

Probabilistic Safety Assessment and Management (PSAM7) and European Safety and Reliability Conference (ESREL), pp.2384-2389, Berlin

112. Mosleh, A. Golfeiz, E. B., 1999, "An approach for assessing the impact of organizational factors on risk", *Technical Research Report*, Center for technology Risk Studies, University of Maryland at college park

113. Mosleh, A., Wang, C., Groth, K., Mohagehgh, Z., 2005, "Integrated Methodology for Identification , Classification and Assessment of Aviation system Risk", *Prepared for Federal Aviation Administration (FAA)*,Center for Risk and Reliability

114. Mosleh, A., Zhu , D., Hu, Y., Nejad, H., 2007, SimPRA (Simulation-based Probabilistic Risk Assessment System)", US Patent Pending, University of Maryland

115. Mumford , M. D., & Espejo, J., 2007, "Cluster Analysis ", In C. Ostroff & T.A. Judge (Eds.), *Perspectives on organizational Fit*, Chapter 11.5, NJ: Erlbaum

116. Ostroff, C., Kinicki, A., Tamkins, M., 2003, Organizational Culture and Climate, in W.C. Borman, D.R. Ilgen, & R.j. Klimoski, (Eds) , *Comprehensive Handbook of Psychology*, Vol. 12: I/O Psychology . Wiley & Sons.

117. Ostroff, C, Schulte,M. (in press), "Multiple Perspectives of Fit in Organization Across Levels of Analysis", In Ostroff, C. & Judge, T.A. (Eds.), *Perspectives on Organizational Fit,* NJ: Erlbaum

118. Ostorm, C., Wilhelmsen, O.C., & Kaplan, B.,1993,"Assessing safety culture", *Nuclear Safety*, Vol. 65, pp. 163-172

119. Ouchi, W. G., 1981, *Theory Z: How American Business Can Meet the Japanese Challenge*, Reading, MA: Addison-Wesley

120. Pate-Cornell, M.E. & Murphy, D.M., ,1996, "Human and Management Factors in Probabilistic Risk Analysis: The SAM approach and Observations from Recent Application", *Reliability Engineering and System Safety*, Vol. 53, No. 2, pp. 115-126

121. Perrow, C., 1984, *Normal Accidents*, Inc. Publishers, New York

122. Peters, T.J., & Waterman, R., 1982, *In search of Excellence*, New York: Harper and Row

123. Peterson, D., 1988, *Safety Management*, Aloray Inc., New York

124. Pidgeon, N.F. ,1991, “safety culture and risk management in organizations”, *Journal of cross- cultural Psychology*, Vol. 22, No. 1, pp. 129-140

125. Pritchard, R.D., & Karasick, B.W. ,1973, “The effects of organizational climate on managerial job performance and job satisfaction”, *Organizational Behavior and Human Performance*, Vol. 9, pp. 126-146

126. Quinn, R.E., & McGrath, M.R., 1985, “The transportation of organizational cultures: A competing values perspectives”,. In P. J. Frost, L.F. Moore, M.R. Louis, C.C. Lundberg, & J. Martin (Eds.), *Organizational culture* , pp. 315-334, Beverly Hills, CA:Sage

127. Quinn, R.E., & Rohrbaugh, J., 1983, “A spatial model of effectiveness criteria; Toward a competing values approach to organizational analysis”, *Management Science*, Vol. 29, pp. 363-377

128. Rasmussen, J. , 1997, “Risk Management in a Dynamic Society: a modeling problem”, *Safety Science*, Vol .27,pp.183-213

129. Rauzy, A., 1993, "New Algorithms for Fault Trees Analysis", *Reliability Engineering and System Safety*, Vol. 40, pp. 203-211

130. Rauzy, A., and Y. Dutit, 1997, "Exact and Truncated Computations of Prime Implicants of Coherent and Non-coherent Fault Trees within Aralia", *Reliability Engineering and System Safety,* Vol. 58, pp. 127-144

131. Reason, J., 1990, *Human Error* , Cambridge University Press, New York

132. Reason, J., 1994. “A system approach to organizational error”, *Proceedings of the 12th Triennial Congress of International Ergonomics Association (IEA)*, Vol.1, Toronto, pp.94-96

133. Reason, J., 1997, *Managing the Risks of Organizational Accidents*, Aldershot, Hants, Englnad; Bookfield, Vt., U.S.A.: Ashgate

134. Reason, J., 1998, “Achieving a safe Culture: Theory and Practice”, *Work and Stress*, Vol. 12, pp. 293-306, See p. 294

135. Reason, J., Hobbs, A., 2003, *Managing Maintenance Error*, Ashgate Publishing Company, Aldershot, England

136. Reichers, A.E., & Schneider, B., 1990, “Climate and culture; An evolution of constructs”, In B. Schneider (Ed.) , *Organizational climate and culture* , pp. 5-39, San Francisco; Jossey-Bass

137. Rentsch , J.R. ,1990, "Climate and culture: Interaction and quantitative differences in organizational meanings", *Journal of Applied Psychology*, Vol. 75, pp. 668-681

138. Richmond, B., 2001, *An Introduction to Systems Thinking: STELLA*, High Performance, Inc.

139. Roberts, K.H. & Bea, R., 2001, "Must accidents happen? Lessons form high-reliability organizations", *Academy of Management Executive,* Vol.15, No.3, pp.70-79

140. Roehrig, S., 1993, "Path Analysis and Probabilistic Networks: analogous Concepts", IEEE Transaction , Vol. 3, pp. 523-532

141. Roelen, A. and Wever, R., 2005, "Accident scenarios for an integrated aviation safety model" , *NLR-CR-2005-560*, NLR Amsterdam

142. Roelen, A.L.C. , Wever, R., Hale, A.R., Goossesns, L.H.J., Cooke, R.M., Lopuhaa, R., Simons, M., Valk, P., 2003, "Causal modeling for integrated safety at airports", *Safety and Reliability*, Swets & Zeitlinger, Lisse, ISBN 90 5809 551 7

143. Schneider, B., 1975, "Organizational climates: An essay" , *Personnel Psychology*, Vol.28, pp.447-479

144. Schneider, B., 1987, "The people make the place." *Personnel Psychology,* Vol. 40, pp.437-453

145. Schneider, B., 1990, "The climate for service: An application of the climate construct", In B. Schneider (Ed.) *Organizational climate and culture*, pp. 383-412, San Francisco; Jossey-Bass.

146. Schulte, M., Osroff, C., Kinicki, A., 2006, "Organizational climate systems and psychological climate perceptions: A cross-level study of climate-satisfaction relationship", *Journal of Occupational and Organizational Psychology,* Vol.79, pp.645-671

147. Senge, P.M., 1990, *The Fifth Discipline : the art and practice of the learning organization*, New York: Doubledy

148. Sharit, J., 2000, " A Modeling Framework for Exposing Risks in Complex Systems", *Risk Analysis*, Vol. 20, No.4

149. Siehl, C., & Martin, J., 1990, "Organizational culture: A key to financial performance?", In B. Scneider (Ed.), *Organizational climate and culture,* pp. 241-281, San Francisco: Jossey-Bass

150. Simon, H.A., 1954, "Spurious correlation: a causal interpretation", *J. Amer. Statistic. Assoc.*, Vol. 49, pp. 469-92

151. Sinnamon, R.M., & Andrews, J. D., 1997, "Improved Efficiency in Qualitative Fault Tree Analysis", *Quality and Reliability Engineering International*, Vol. 13, pp. 285-292

152. Smidts, C. , Devooght, J., & Labeay, P.E., 2000, *Dynamic Reliability: Future Direction*, International Workshop on Dynamic Reliability

153. Smillie, R. J. and Ayoub, M.A., 1976, "Accident Causation Theories: A simulation approach", *Journal of Occupational Accidents*, Vo., 1, pp.47-68

154. Spurgin, A.J., Moieni, P. , Gaddy, C.D., Parry, G.W. , Orvis, D.D. , Spurgin, J.P. , Joksimovich, V., Gaver, D.P., and Hannaman, G.W., 1990, *Operator Reliability Experiments Using Power Plant Simulators (Vol. 1-3 Technical Report)*, EPRINP-6937, Palo Alto, California: Electric Power Research institute.

155. Stamatelatos, M. , 2002, *Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners*, Office of safety and Mission Assurance, NASA Headquarters, Washington, DC.

156. Sterman, J., 2000, *Business Dynamics; System Thinking and Modeling for Complex World*, Mc Graw-Hill Companies

157. Suokas, J., 1993, "Hazard and operability study (HAZOP)" In J. Suokas and V. Rouhiainen, (Ed.) , *Quality Management of safety and Risk Analysis*, Elsevier

158. Swain, A.D. & Guttmann, H.E., 1983, *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications* , NUREG/CR-1278: Nuclear Regulatory Commission

159. Tata, J., & Prasad, S., 1998, "Cultural and structural constraints on total quality management implementation", *Total Quality Management*, Vol. 9, pp. 703-710

160. Torres-Toledano, J., & Sucar, L., 1998, "Bayesian Networks for Reliability Analysis of Complex Systems", In *Lecture Notes in Artificial Intelligence 1484*. Springer Verlag

161. Trice, H.M., & Beyer, J.M., 1993, *The cultures of work organizations*, Englewood Cliffs, NJ: Prentice Hall

162. *U.S. Nuclear Regulatory Commission, Reactor Safety Study: An Assessment of Accidents in U.S. Commercial Nuclear Power Plants*, 1975, U.S. Regulatory Commission, WASH-1400, Washington , D.C.

163. Veeraraghavan, M., and K.S. Trivedi, 1994, "Combinatorial Algorithm for Performance and Reliability Analysis Using Multistate Models", *IEEE Trans. Computers*, Vol. 43, No. 2, pp. 229-234

164. Vurren, W., 2000, " Cultural influences on risks and risk management; six case studies", *Safety Science*, Vol. 34 , pp. 31-45

165. Walton, M., 1986, *The Deming Management Method*, New York: Putnam

166. Wang, C., 2007, *Hybrid Causal Methodology for Risk assessment*, Ph.D thesis, University of Maryland, Center for Risk and Reliability

167. Weick, K., Sutcliffe, K., 2001, *Managing the Unexpected: Assuring High Performance in an Age of Complexity*, John Wiely & Sons, Inc.

168. Westrum, R., 1992, "Culture with requisite imagination", in J.A. Wise, V.D. Hopkin and P. Stager (Eds.), *Verification and Validation of complex Systems: Human Factors Issues*, Berlin: Springer-Verlag, pp. 401-16

169. Whetten, D. A., 1989, "what constitutes a theoretical contribution?", *Academy of Management Review*, Vol. 14, No. 4, pp. 490-495

170. Wickens, C.D., Gordon, S.E., & Liu, Y., 1997, *An Introduction to Human Factors Engineering*, New York: Addison-Wesley Educational Publishers Inc.

171. Wickens, C., Hollands, J., 2000, *Engineering Psychology and Human Performance,* Prentice Hall, New Jersey

172. Wiegmann, D. , Zhang H., Thaden, T., Sharma, G., and Mitchell, A., 2002, "Safety Culture: A review", *Technical Report ARL-02-3/FAA-02-2*, Federal Aviation Administration

173. Wiegmann, D., Shappell, S. , 2000, "The Human Factors Analysis and Classification System- HFACS," Office of Aviation Medicine Technical Report No, DOT/FAA/AM-00/7, Civil Aeromedical Institute, Oklahoma City, OK, February

174. Wood, A.P., 1985, "Multistate Block Diagrams and Fault Trees", *IEEE Trans. Reliability*, Vol. 34, pp. 236-240

175. Yu, J., Ahn, N., Jae, M. 2004, " A Quantitative Assessment of Organizational Factors Affecting safety Using system Dynamics Model", *Journal of the Korean Nuclear Society*, Vol.36, No.1, pp. 64-72

176. Yu, K., I. Koren, and Y. Guo, 1994, "Generalized Multistate Monotone Coherent Systems", *IEEE Trans. Reliability*, Vol. 43, No. 2, pp. 242-250

177. Zang, X., D.Wang, H. Sun, and K. Trivedi, 2003, "A BDD-Based Algorithm for Analysis of Multistate Systems with Multistate Components", *IEEE Trans. Computers*, Vol. 52, No. 12, pp.1608-1618

178. Zhu, D., 2005. Integrating Software Behavior Into Dynamic probabilistic Risk Assessment, Ph.D thesis, University of Maryland, Center for Risk and Reliability

179. Zink, K.J ,1995, *Total Quality Management as a Holistic Management Concept: The European Model for Business Excellence*, Springer, London

180. Zohar, D., 1980, "Safety Climate in Industrial Organizations: theoretical and Applied Implications", *Journal of Applied Psychology*, Vol. 65, pp.96-102

181. Zohar, D. ,2000, "A Group-level Model of Safety Climate ; Testing The Effects of Group Climate on Micro accidents in Manufacturing Jobs", *Journal Of Applied Psychology*, Vol. 85, pp.587-596

182. Zohar, D., 2003, "Safety climate: Conceptual and measurement issues", In J.C.T. Quick , L.E., (Ed.) , *handbook of Occupational Health Psychology,* pp.123-142, Washington: American Psychological Association

183. Zohar, D., & Luria , G., 2005, "A Multilevel Model of Safety Climate : Cross-Level Relationships Between Organization and Group-Level Climates", *Journal of Applied Psychology*, Vol.90, No.4, 616-628

184. Φien, K., 2001, "A Focused Literature Review of Organizational Factors' Effect on Risk", in *Risk Control of Offshore Installations : A framework for the Establishment of Risk Indicators*, Doctoral Thesis, The Norwegian University of Science and Technology