A STUDY OF SAFETY CULTURE ASSESSMENT FRAMEWORK FOR PROCESS INDUSTRIES AND ITS APPLICATION TO A BAYESIAN BELIEF NETWORK ANALYSIS

A Thesis

by

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ABSTRACT

Investigations of major catastrophes in process industries have revealed that deficiency of good safety culture is one of the underlying causes of such disasters. Not only has safety culture been recognized as a root cause, but also it is increasingly accepted as an influential factor in a risk analysis and considered as a legal requirement. Most of current quantitative risk analyses (QRA) rely on technical factors but more and more effort is being made for the incorporation of human and organizational factors (HOFs). Especially, safety culture largely represents an organizational attitude towards safety. Thus, how to measure safety culture in more effective manners and how to utilize such assessment data in a QRA are chosen as major objectives of this research. For the measurement of safety culture, this study suggests an approach that assesses values and assumptions by looking through artifacts, *e.g.*, management level and employee's behavior. Such approach employs following two methods: a matrix structure composed of safety culture dimensions, and grading schemes that provide different levels of safety practices. Using such an approach and suggested methods, a safety culture assessment questionnaire is developed as a results. For the incorporation of such safety culture data into a risk analysis, this study employs a risk model based on Hybrid Causal Logic (HCL) and a Bayesian Belief Network (BBN) to represent cause and effect relationships among variables. Mock-up safety culture data is generated for this analysis. Findings from investigation of Universal Form Clamp incident (2006) are used to establish a case scenario upon which a fault tree and an event tree are constructed. To make a transition

from qualitative knowledge about safety culture to quantitative probability data, some of the safety culture dimensions are selected as Risk Influencing Factors (RIFs), while Safety Culture Influencing Factors (SCIFs) are developed and introduced in this work. Using the established BBN, prior generic probability data are updated with newly obtained evidences such as mock-up safety culture assessment data. In addition, several analyses, *e.g.*, predictive and diagnostic reasoning are conducted to determine how a change in safety culture affects the probabilities of safety-related events and also to identify which safety culture aspects need improvement.

DEDICATION

To my committee members,

Dr. M. Sam Mannan, Dr. Chad V. Mashuga and Dr. Maria A. Barrufet,

To my parents,

Sukwoo Son, Yongho Seo and Siyeon Kim,

To my wife,

Soyun Park,

And

To my children,

Yoonsuh, Yeonjae and Yongbeom Son.

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NOMENCLATURE

AIChE	American Institute of Chemical Engineers
B(B)N	Bayesian (Belief) Network
BSEE	Bureau of Safety and Environmental Enforcement
CCPS	Center for Chemical Process Safety
CSB	Chemical Safety Board
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
HCL	Hybrid Causal Logic
HMI	Human Machine Interaction
HOF	Human and Organizational Factor
IAEA	International Atomic Energy Agency
INSAG	International Nuclear Safety Group
LoC	Loss of Containment
LoRF	Layers of Risk Factors
NASA	National Astronautic and Space
NPT	Node Probability Table
QRA	Quantitative Risk Analysis
RBPS	Risk Based Process Safety
RIF	Risk Influencing Factor
SCIF	Safety Culture Influencing Factor

SEMS	Safety and Environmental Management Systems
SoTeRiA	Socio-Technical Risk Assessment
UK HSE	United Kingdom Health and Safety Executive
US NRC	United States Nuclear Regulatory Commission
VCE	Vapor Cloud Explosion

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1. INTRODUCTION

Safety culture becomes a frequently used term in many areas of loss prevention and risk management practices such as in incident investigations, trainings and behavior-based safety programs. Often times, people take advantage of mentioning safety culture as a catch-all term to describe organizational issues that are not easily delineated by the failure of equipment. Due to relentless efforts of social scientists, psychologists and engineering researchers, knowledge about safety culture has been accumulated enough to provide usefulness in several areas. Therefore, safety culture is widely utilized for the improvement of safety management systems of various organizations. For example, Shell launched Hearts & Minds project to develop a generative safety culture in which employees motivate themselves to behave safely [1]. Other examples of taking benefits of safety culture studies are found in the development of socio-technical risk analysis, *e.g.*, SoTeRiA [2] and in the legislation of safety culture assessment regulations [3].

Among realms of studies associated with safety culture, its definition and measurement have long been an academic research topic. The progress in this topic seems to start from a common tenet trusted and often quoted by management thinker, *e.g.*, Peter Drucker that *you cannot manage what you cannot measure* [4]. So far, several philosophies and forms of safety culture measurement have been developed. However, attempts to view safety in an engineering perspective and to apply it to quantitative risk analysis (QRA) are still necessary to make safety culture assessment a handy tool for engineers and managers, particularly who are working in process industries.

1.1 Background

Investigations of major industrial catastrophes along the history have revealed that deficiency of good safety culture is one of the underlying causes of such disasters. To begin with, the term, *safety culture*, made its first appearance after Chernobyl Nuclear incident took place in 1986. According to the incident investigation report [5] published by the International Atomic Energy Agency (IAEA), poor safety culture in that nuclear power plant was one of the contributing factors to the incident. Since its advent, the term and concept of safety culture have begun to be widely accepted by others such as chemical & petroleum processing and aerospace industries. For instance, Texas City refinery explosion in 2005 exemplifies how lack of safety culture across its U.S. refineries can override its safety management system and align all the '*Swiss Cheese*' holes [6] of safety barriers in a straight line. Examples of those incidents resulting from cultural factors are listed in Table 1.

Table 1. A List of Incidents Resulting from Cultural Factors

Industry	Name of Incident	Year	Issues regarding Safety Culture
Oil & gas	La Porte Mercaptan Release	2014	Despite the DuPont's reputation about its world-class safety culture, multiple incidents at the facility indicated collapsed safety programs [7].
	Macondo Well Explosion and Fire	2010	Flaws in offshore safety regulation, *e.g.*, SEMS, allowed those companies of less mature safety culture to fail in identifying major hazards [8].

Table 1 Continued

Industry	Name of Incident	Year	Issues regarding Safety Culture
Oil & gas	Texas City Refinery Explosion	2005	Discrepancies among BP's five U.S. refineries showed that there was no consistent effort for maintaining the corporate safety culture [9].
	Piper Alpha Explosion and Fire	1988	The incident epitomized the aftermath of production-oriented corporate culture where plant's shutdown meant huge production loss and associated cost [10].
Nuclear	Fukushima Nuclear Incident	2011	The nuclear plant had notable deviations in implementing international practices regarding hazard evaluation, high consequence events management and safety culture [11].
	Chernobyl Nuclear Incident	1986	The Chernobyl disaster resulted largely from insufficient safety culture at not only national perspective but also locally [12].
Aerospace	Columbia Incident	2003	Complacency and unsupported confidence have brought shortcomings in safety culture that hindered asking about and capturing potential risks of foam insulation [13].
	Challenger Incident	1986	
Aviation	Valujet Airlines Flight 592	1996	Valujet's fast economic success may have caused corporate culture with insufficient rigor for achieving high level of safety [14].
	Continental Express Flight 2574	1991	The underlying causal factor seems to be the failure of management to maintain corporate culture which was supposed to encourage and enforce compliance with maintenance and quality assurance programs [15].

Not only safety culture has been recognized as a root cause of an incident, but also it is increasingly being accepted as one of the factors that are considered in a risk analysis. Most of conventional quantitative risk analyses (QRA) rely upon technical factors that typically address hardware elements, *e.g.*, equipment, material and process, of a system. However, more and more attention is paid to human and organizational factors (HOFs) since such technical failures are largely dependent upon human error and a prevailing organizational attitude that underlies towards safety, or safety culture.

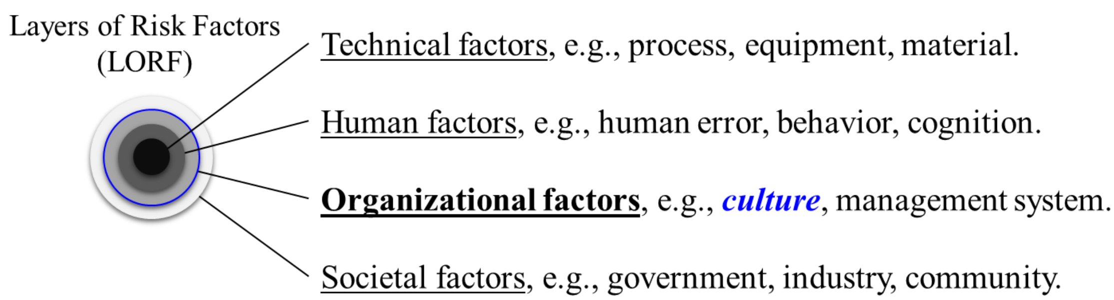

Figure 1. Layers of Risks Factors

In order to illustrate the relationship of these factors, I am proposing a notion called Layers of Risk Factors (LORF) as presented in Figure 1. In theory, societal factors, *e.g.*, regulatory bodies and industry associations should be taken into account in a risk analysis. The present study, however, limits its focus on both technical and organizational factor to highlight how those two can be amalgamated in a risk analysis. The question that comes up next is how such integration is made possible. Eq. (1)[16] proposes an approach that qualitatively represents that safety culture can be embraced in the well-known risk function. This equation simply and intuitively explains the inverse relationship between safety culture and risk. However, considering the complexity associated with calculation of risks, quantifying safety culture in engineering terms still remains onerous.

$$\text{Risk} = \frac{\text{Consequence } \times \text{Frequency}}{Safety\ Culture} \qquad \text{Eq. (1)}$$

Much of effort for conducting research in safety culture and its application to risk management has been voluntary by professional organizations and academia [17, 18]. In addition, regulators are pondering process safety culture assessment as a legal requirement for oil and gas industries. For example, the State of California offered a proposal [3] for the revision of Process Safety Management for Petroleum Refineries, which includes a mandatory execution of Process Safety Culture Assessment (PSCA). According to the proposed Safety Order, an employer shall develop, implement and maintain PSCA program. The employer shall conduct PSCA every five years and they shall ensure that PSCA addresses hazards reporting and implementation of an incentive scheme to encourage reporting and prioritizing process safety during upset or emergency situation. The employer also shall develop a written report and implement the recommendations. Yet, it is quite uncertain what changes are made to the proposed Safety Order during a law-making process but it is believed that this study gives useful guidance to companies in preparation for a safety culture assessment tool in advance before such law becomes effective.

To summarize, the role of safety culture is becoming crucial in process industries in that it is considered as a root cause of incidents, a risk factor and a requirement. In this regard, examining methods of measuring safety culture and incorporating it into a risk analysis will provide a meaningful contribution to managing socio-technical risks in process industries.

1.2 Problem Statement

In spite of increasing demand on research about safety culture as mentioned in the previous section, there exist rooms for improving safety culture assessment tools. In overall, three main gaps have been identified through the literature review. Firstly, there is lack of consensus among dimensions of safety culture/climate assessment [19]. There are a plethora of studies that provide a set of dimensions by which safety climate is assessed. Nevertheless, many of them cover simplified and partial aspects of safety climate [20, 21]. Besides, safety climate, as its name suggests, represents perceived status about safety in an organization whereas safety culture refers to deeply rooted attitude towards safety that members of the organization take for granted. Furthermore, few were developed for the assessment of process safety culture.

Secondly, a question is raised in terms of grading scale. Most of safety climate measurement tools employ 5-point Likert scale. This scale asks a person how much he/she agrees with the statement by assigning a number at each answer, for example, one (1) being strongly disagree and five (5) being strongly agree. Because an individual's answer is based upon his or her perception about safety, the answer is likely to be subjective and thus unstable depending on his or her past experience and particular memory that pertains to a specific topic being questioned.

Finally, it is observed that there is an increasing demand on the incorporation of human and organizational factors into quantitative risk analysis (QRA). The importance of a human-being's role as a designer of the system, an operator of the facility and a respondent to an emergency is rapidly growing in the process industries as the complexity of those industries increases. As such, safety culture, which heavily affects human performance, begins to be considered as a crucial factor in QRA. The simple concept for this relation is previously introduced in Eq. (1). Basically, conventional QRA views risk as a product of consequence and frequency of a certain event. That equation intuitively includes safety culture as a denominator so its reciprocal is proportional to risk. However, this concept has yet been validated and therefore more research effort is required to pinpoint the exact quantitative correlation between risks and the level of safety culture. Nevertheless, it is propitious that some researchers have been conducting socio-technical risk assessment studies such as SoTeRiA (Socio-Technical Risk Assessment) [2, 22] where technical, human and organizational factors are assessed altogether.

1.3 Research Objectives

The main goals of the present work are to develop a more structured method of measuring safety culture, and to demonstrate how the assessment results can be used in a quantitative risk analysis. In order to serve this purpose and appropriately address the gaps identified in the previous section, this research has the following objectives:

1) To propose a framework of how safety culture in process industries can be effectively measured. This framework aims at providing its users a more comprehensive understanding about the status of safety culture.
2) To provide a set of questions to assess safety culture based on the proposed framework. Measurement of performance often takes advantages of pre-determined sets of questions to ask. The questionnaire can serve different usages such as employee survey, one-on-one interview or a combination with safety systems audit.
3) To perform a socio-technical quantitative risk analysis of a chemical process operation using case scenarios and a Bayesian Belief Network (BBN). The BBN enables to put organizational attributes and technical factors together for a risk analysis. Comparisons between BBN-based results and conventional risk analysis outcomes are provided. Also, predictive and diagnostic reasoning is performed from the baseline BBN model.

2. LITERATURE REVIEW

2.1 Safety Culture & Climate

2.1.1 Definition of Safety Culture

Safety culture is a subset of organizational culture [23]. Thus, safety culture should not be understood as a stand-alone concept or the only lens through which safety behavior of a group is viewed. The culture of an organization is defined as "a pattern of shared basic assumptions learned by a group [24]." Despite the covert nature of organizational culture, it expresses itself as observable things such as written documents, behaviors of its members, organizational structures, procedures and physical arrangement of equipment and facilities. Originally, Schein (1990) developed this concept by proposing three fundamental levels of organizational culture: artifacts, espoused beliefs and values, and underlying assumptions [24]. Likewise, these layers of safety culture should be approached in different manners to understand how safety culture gets formed, fostered and improved, or deteriorated.

It is found that safety culture is defined in various ways through literature review. The term of safety culture made its first emergence in the Chernobyl nuclear incident investigation report [5] published in 1986 by the International Nuclear Safety Group (INSAG), convened and guided by the International Atomic Energy Authority (IAEA). The IAEA, later in 1991, defined safety culture as the "assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance [25]". United States Nuclear Regulatory Commission (US NRC) gives an even finer definition about nuclear safety culture:

"Nuclear safety culture is the core values and behaviors resulting from a collective commitment by leaders and individuals to emphasize safety over competing goals to ensure protection of people and the environment". (US NRC, 2015) [26]

US NRC seems to be successful in bringing together the layers of organizational culture by stating not only values but also behaviors, a type of artifacts. In addition, US NRC states who is held responsible for the commitment and what goals they attempt to achieve. The Advisory Committee on the Safety of Nuclear Installations (ACSNI) similarly defines safety culture as "the product of the 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 programs [27]". The Center for Chemical Process Safety (CCPS), a corporate membership organization within AIChE (American Institute of Chemical Engineers), defines process safety culture in its publication [17] as "the combination of group values and behaviors that determine the manner in which process safety is managed." But, CCPS also briefly voices it as "How we behave when no one is watching." Various definitions of safety culture are chronologically enumerated in Table 2.

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Table 2. Definitions of Safety Culture

Author (year)	Definition of Safety Culture
Cox & Cox (1991)[28]	Safety culture reflects the attitudes, beliefs, perceptions, and values that employees share in relation to safety.
INSAG (1991)[25]	Assembly of characteristics and attitudes in organizations and individuals that establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance.
Pidgeon (1991)[29]	The set of beliefs, norms, attitudes, roles, and social and technical practices that are concerned with minimizing the exposure of employees, managers, customers and members of the public to conditions considered dangerous or injurious.
Ostrom *et al*. (1993)[30]	The concept that the organization's beliefs and attitudes, manifested in actions, policies, and procedures, affect its safety performance.
Guldenmund (2000)[31]	Those aspects of the organizational culture which will impact on attitudes and behavior related to increasing or decreasing risk.
Lee & Harrison (2000)[32]	The values, attitudes, beliefs, risk-perceptions and behaviors as they relate to employee safety.
Richter & Koch (2004)[33]	The shared and learned meanings, experiences and interpretations of work and safety — expressed partially, symbolically—which guide people's actions towards risks, accidents and prevention.
Fang *et al*. (2006)[34]	A set of prevailing indicators, beliefs, and values that the organization owns in safety.

Table 2 Continued

Author (year)	Definition of Safety Culture
CCPS (2007)[17]	The combination of group values and behaviors that determine the manner in which process safety is managed.
BSEE (2013)[35]	The core values and behaviors of all members of an organization that reflect a commitment to conducting business in a safe and environmentally responsible manner.
Mentzer *et al.* (2014)[36]	An organization's shared attitudes, values, norms and beliefs about safety, including attitudes about danger, risk, and the proper conduct of hazardous operations.
US NRC (2015)[26]	Nuclear safety culture is the core values and behaviors resulting from a collective commitment by leaders and individuals to emphasize safety over competing goals to ensure protection of people and the environment.

2.1.2 Safety Culture vs. Safety Climate

Safety climate, largely welcomed and employed by psychologists, is a commonly used term to describe safety culture during a short period of time. Many of the literature distinctively differentiates safety culture from safety climate, however, those two terms, in many cases, are utilized interchangeably [37]. Safety climate is considered to be a manifestation of safety culture in the behavior and attitude of employees [37]. The term, safety climate, began to gain its popularity when Zohar (1980) published his research paper about theoretical and applied implications about safety climate in different industries in Israel [38]. Zohar, who developed and attempted the first measure of safety climate, conceptualized it as a subset of organization climate and he defined it as “molar perceptions” that members of an organization possess about the surrounding situation [38]. More and more researchers after him ventured to assess safety climate and tried to figure out how safety climate is manifested within an organization. The most widely accepted concept of safety climate is that it is the way how people perceive the safety culture of the organization they belong to. For example, the UK Health and Safety Executive (HSE) defines it as the “tangible outputs or indicators” of corporate safety culture, which is accepted by individual members or a group of people at a certain period of time [39]. Cooper (2000) classifies safety climate as one of constituent aspects of safety culture [40]. His classification of safety culture is illustrated in Figure 2.

Since safety climate is concerned with the perception of individual members of the organization, it is likely to be unstable and changeable over times. The way that safety climate is formed can be influenced by the policies and practices that those organizations put in place [41].

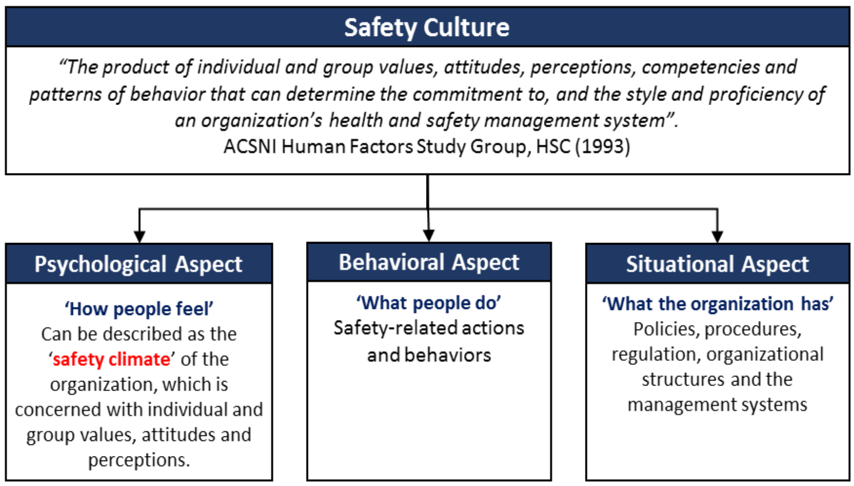


Figure 2. Three Aspects of Safety Culture (Cooper, 2000)

It is a common belief that safety climate influences the occurrence of incidents at work and vice versa. Namely, safety climate can be a leading indicator, *e.g.*, good safety climate that precedes low incident rate, but also it can be a lagging indicator, *e.g.*, a series of incidents or fatality which, as a result, deteriorates safety climate [42]. In most cases, safety climate is determined by applying questionnaires about given safety focuses, *i.e.*, the attitude and behavior of an employee's supervisor. Bergman *et al.* (2014) further investigate the 'shelf life' of safety climate assessment. Their finding is that the validity of safety climate measurement expires only after a few months [43]. To sum this all up, safety climate is the foreground where things associated with safety emerge above the surface while safety culture is regarded as the background which underlies at the bottom of the organization [18]. This relationship between safety culture and safety climate is often depicted through an analogy of an iceberg as illustrated in Figure 3 (the picture is taken from [44]). Safety climate is the part seen above the surface and corresponds to artifacts. This pertains to observed behaviors of the members, written documents such as policy statements, work procedures and signs/banners, and formal structure and system of an organization. On the contrary, safety culture is a tacit attribute of the organization. Safety culture is associated with intention and motivation of the behavior, value and belief upon which policies and procedures are established, and deeply rooted assumptions that members of the organization take for granted.

Figure 3. Iceberg of Safety Culture and Safety Climate (Picture from Riley, 2015)

Wiegmann *et al.* (2004) provide an integral view about both safety culture and safety climate through extensive literature review [45]. They suggest some commonalities that exist across the literature regarding safety culture and safety climate, respectively. The summary of such commonalities is made in Table 3. In addition to the iceberg analogy, this work shows more sophisticated and discernible characteristics of two terms in relation to members, organizational systems and responsiveness to change.

Table 3. Commonality of Safety Culture/Climate Studies (Wiegmann *et al.*, 2004)

Safety Culture	Safety Climate
• A concept defined at a group level. • Shared values among all the group or organization members. • Concerned with formal safety issues. • Closely related to the management and supervisory systems. • Emphasize the contribution from everyone at every level. • Impact members' behavior at work. • Reflected in the contingency between reward systems and safety performance. • Organization's willingness to learn from errors and incidents. • Enduring, stable and resistant to change.	• A psychological phenomenon defined at a particular time. • Concerned with intangible issues such as situational and environmental factors. • Temporary manifestation or *snap shot* of safety culture. • Unstable and subject to change.

By the reticent nature of organizational culture, measuring directly safety culture of an organization is challenging, and also the relationship between safety culture and the causation of industrial incidents has yet been clearly proven so far. Instead, a number of researchers employ safety climate as a yardstick to measure safety culture at a specific period of time.

2.1.3 Safety Climate Survey Tools

Based on the knowledge that safety climate is employees' perception about safety, safety climate is commonly assessed through employee surveys [42]. Zohar (1980) made the first attempt to measure safety climate by making use of a questionnaire that he created. He developed 40 items based on seven organizational dimensions. Since then, many other advocates of safety climate began to design safety climate questionnaires and put them into use. A summary of some of those safety climate studies is presented in Table 4.

Since a questionnaire is the most common medium adopted for safety climate assessment [46], there are several things to consider in designing and conducting the survey. For instance, the design of such questionnaire for assessment should take into consideration the length of questions and the number of people surveyed. Other instruments such as interview and audit are utilized from time to time in cases where more thorough assessment is required. However, using interview and/or audit for safety climate assessment is a lengthy process and also requires a group of experts knowledgeable in overall safety management systems and safety culture. Once the type of instrument has been determined, the scope of assessment is discussed as to how many employees are involved in the survey and at which organizational level safety climate is assessed. The number of people who are asked to do a survey depends upon statistical settings such as confidence levels. However, when it comes to organizational levels of the assessment, the approach is not straightforward and it is necessary to consider how people in different levels perceive things differently. With this regard, Guldenmund (2007) employed three levels of safety climate: organizational, group and individual [46]. He viewed that each level of an organization represents different safety climate. In other words, one measurement tool used for a certain level may not be directly applicable to another level of organization. However, this study does not attempt to provide separate approaches for such different levels. Whereas things mentioned above are related to the shape of an assessment, dimensions of the assessment deal with its content. If the former means *how* the survey is carried out, the latter indicates *what* is measured. As seen in the Table 4, some dimensions such as management commitment and communication are quite common among literatures but a majority of them differ from one another. In addition, most of safety climate instruments adopt 5-point Likert scale to measure the subject's evaluation about a statement or a question. By assigning a different discrete value on each choice, Likert scale can take the semi-quantitative form. One of the significant differences of this research from 5-point scale is that this study does not employ 5-point scale or similar scale scheme. Rather, this study suggests a list of specific answers that represent different levels of company safety value.

Table 4. Summary of Safety Climate Assessment Tools

Researcher(s) / Name	Industry / Country	Dimensions (factors)	Number of Items	Scale
Gao *et al.* (2015)[47]	Aviation / Asia-Pacific region	• Safety philosophy • Safety reporting • Safety feedback • Safety promotion & communication	33 items	5-point
Nielsen *et al.* (2013)[48]	Petro-Maritime / Norway	• Safety prioritization • Safety management and involvement • Safety vs. production • Individual motivation • System comprehension	35 items	5-point
Sparer *et al.* (2013)[49]	Construction / US	• Safety climate • Worker involvement • Management involvement	9 items	100-point
Bosak *et al.* (2013)[50]	Chemical / South Africa	• Management commitment to safety • Priority of safety on plant • Pressure for production	26 items	5-point

Table 4 Continued

Researcher(s) / Name	Industry / Country	Dimensions (factors)	Number of Items	Scale
US NRC (2009)[51]	Nuclear / US	• Clarity of responsibilities • Management leadership • Supervision • Working relationship • Empowerment • Communication • Workload and support • Training and development • Performance management • Job satisfaction • Engagement • NRC mission and strategic plan • NRC image • Organizational change • Continuous improvement commitment • Quality focus • Open, collaborative work environment	145 items	100-percent

Table 4 Continued

Researcher(s) / Name	Industry / Country	Dimensions (factors)	Number of Items	Scale
Vinodkumar & Bhasi (2009)[52]	Chemical / India	• Management commitment and actions for safety • Workers' knowledge and compliance to safety • Workers' attitudes towards safety • Workers' participation and commitment to safety • Safeness of work environment • Emergency preparedness in the organization • Priority for safety over production • Risk justification	54 items	5-point
Wu *et al.* (2009)[53]	Petrochemical /Taiwan	• Safety Leadership : Safety coaching, caring and controlling • Safety Climate : Employee commitment, risk perception and emergency response • Safety Performance : Safety inspection, accident investigation, training and safety motivation	46 items	5-point

Table 4 Continued

Researcher(s) / Name	Industry / Country	Dimensions (factors)	Number of Items	Scale
Lin *et al.* (2008)[54]	Multiple industries *e.g.*, construction, refinery, cement production. / China	• Safety awareness and competency • Safety communication • Organizational environment • Management support • Risk judgment • Safety precautions • Safety training	21 items	5-point
Neal & Griffin (2006)[55]	Healthcare / Australia	• Safety climate • Safety motivation • Safety compliance • Safety Participation	12 items	5-point

Table 4 Continued

Researcher(s) / Name	Industry / Country	Dimensions (factors)	Number of Items	Scale
UK Health and Safety Executive (2002)[56] / CST (Climate Survey Tool)	General / Worldwide	• Organizational commitment and communication • Line management commitment • Supervisor's role • Personal role • Work mates' influence • Competence • Risk taking behavior and some contributory influences • Obstacles to safe behavior • Permit-to-work system • Reporting of accidents and near misses	71 items	5-point
Robert Gordon University & Aberdeen University (1998)[57] / OSCQ (Offshore Safety Climate Questionnaire)	Offshore / Worldwide	• Job • Risk perception – main/work task hazards • Assessment of safety • Safety attitude • Contractor safety attitude • Job security • Accident history	153 items	5-point

Table 4 Continued

Researcher(s) / Name	Industry / Country	Dimensions (factors)	Number of Items	Scale
Donald & Canter (1994)[58] / SAQ (Safety Attitude Questionnaire)	Chemical / UK	• People : Self, workmates, supervisor, manager and safety representative • Attitude behavior : Knowledge, satisfaction and execution • Activity : Passive/active	167 items	5-point
Zohar (1980)[38]	Multiple industries *e.g.*, metal fabrication, food processing, chemical, etc.	• Perceived importance of safety training programs • Perceived management attitudes toward safety • Perceived effects of safe conduct on promotion • Perceived level of risk at work place • Perceived effects of required work pace on safety • Perceived status of safety officer • Perceived effects of safe conduct on social status • Perceived status of safety committee	40 items	5-point

2.1.4 Characteristics of Good Safety Culture

Knowing what characterizes good safety culture is crucial because it gives better idea of how to select dimensions of safety culture assessment. Several authors proposed a group of traits of a company with good safety culture. Mannan *et al.* (2013) presented ten characteristics of best-in-class safety culture [59]. Those characteristics are compared with those of UK Health and Safety Executive (HSE) [60] and Center for Chemical Process Safety (CCPS)'s Risk Based Process Safety (RBPS) [17] in Table 5. To make the comparison easier, elements of UK HSE and CCPS are re-ordered to fit Mannan *et al.*'s list. In spite of variations in wording, most of the elements are commonly addressed.

A company with good safety culture is not only distinguished by its safety performance but also the *health* of the organization. Healthy safety culture is largely driven by strong leadership and unyielding management commitment to safety. How committed the top management is to safety often determines the success of safety initiatives and the allocation of resource that is required to achieve such initiatives. Effective safety leaders, who lead by example, influence other members in an organization in the way they accept the value of safety and behave in safe manners. When those leaders demonstrate their commitment to safety through appropriate actions and supports, other people start to follow such actions and consider safety as a core value. In addition, excellence of safety leadership is characterized by how successfully management creates safety mission and vision, and renders them embedded throughout the organization. Also, assigning clear roles and responsibilities for all levels in the organizational structure is another key task that leaders should assume [61]. This guides each member to get specific knowledge of what to act for safety.

Once management possesses strong commitment to safety, it cascades down through each level of the organization. Consequently, people begin to accept safety as a value, not a priority. A value is something that is not traded off when different priorities are competing each other. For instance, if more production can be compensated by less quality of a product, then those two play as a priority.

On the contrary, when safety is recognized as a value, people do not compromise safety with any other priorities irrespective of the consequence of their decision. In the long run, they have a robust conviction that safety would bring the greater good such as the protection of human lives, enhancement of their health, and the pursuit of happiness. As safety culture is shared by members of a group, their participation, often enabled and facilitated by valiant empowerment from managers and supervisors, is of paramount importance. Employees' activities at the grassroots in the organization make sure that safety initiatives are not only *talked* in the document but also *walked* in practice. Their involvement also ensures to catch weak signal that otherwise may snowball to a large process mishap such as loss of containment (LoC).

In order to catalyze the interaction between management and employees, formal arrangements, for instance, communication channels at all levels of the organization should be made. Two-way and open communication including reporting incidents and sharing lessons learned are also common traits of an organization having mature safety culture. Such organization often accommodates high standards and exemplary practices that go beyond compliance with given standards and regulations. In addition to these features, healthy safety culture is sustained by continuously and stringently monitoring safety performance and by elevating safety awareness of its members. This monitoring helps identify the current status of safety culture and provide feedback to its members and work processes of the organization.

Since these properties of good safety culture are derived from lessons learned through history and best practices of organizations with excellent safety programs [59], those characteristics proposed in the literature represent just an ideal condition which is not easily captured in one organization, but they are worth being pursued in every organization. With that being said, the ideally expected features will be used to measure safety culture against. This study largely employs Mannan *et al.*'s work [59] but also attempts to take advantage of the guidelines presented in the CCPS RBPS [17], so such approach helps make the safety culture measurement more relevant to process industries.

Table 5. A Comparison of Characteristics of Safety Culture

No.	UK HSE (2001) [60]	Mannan *et. al.* (2013)[59]	CCPS RBPS (2007)[17]
1	Management commitment and visibility	Leadership	Strong leadership
2	Productivity versus safety	Culture & value	Process safety as a core value
3	Shared perceptions about safety	Goals, policies & initiative	
4		Organization and structure	Documentation of process safety culture emphasis and approach
5	Participation	Employee engagement and behaviors	Empowerment to individuals / Defer to expertise
6	Safety resources	Resource allocation and performance management	
7		Systems, standards and processes	High standards of performance
8	Communication	Metrics and reporting	Open and effective communication / Timely response to process safety issues and concerns
9	Learning organization/ Training	A continually learning organization	A questioning/learning environment
10		Verification and audit	Continuous monitoring of performance
11	Trust		Mutual trust
12			A sense of vulnerability

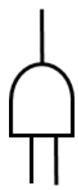
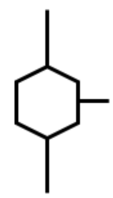
2.2 Quantitative Risk Analysis

As the complexity associated with hazardous operations in process industries increases, the quantification of risks is gaining more popularity to support decisions critical to the safe conduct of such operations. Quantitative Risk Analysis, as its name suggests, is a method that numerically calculates risks in terms of the frequency and the consequence of an event. Conventional or traditional QRA has long been considered technical aspects of a system [62]. However, the roles of human and organizational factors (HOFs) have become pivotal to ensure to maintain the overall system integrity of the facility. In order to include the HOFs into the QRA, the following analysis methodologies are employed.

2.2.1 Fault Tree Analysis (FTA)

Firstly introduced by H.A. Watson of Bell Telephone Laboratories in 1961, fault tree analysis represents the structure of a failure event by investigating its component as causes [63]. Being a deductive approach, FTA starts from the failure or abnormal event on the top of the tree and examines downward by identifying its parts or subsystems. Such examination continues until failing base elements are obtained and those elements are not able to be decomposed into any smaller entities [64]. Fault tree employs several logic gates to explain the relationship between input and output events. The functions and typical symbols of some common logic gates are presented in Table 6. Since fault tree analysis has the top event at its peak and constituent parts below, the overall structure appears to be a tree. Therefore, input events are placed lower than output ones in the tree. A cut set in FTA is defined as a combination of component failures that lead to a system breakdown and it is called a minimal cut set when the system fails if and only if all of the components of the set fail [65].

Table 6. Common Logic Gates of a Fault Tree

AND	OR	Exclusive OR	Priority AND	Inhibit
				
Output occurs if all inputs occur.	Output occurs if any of inputs occurs.	Output occurs if only one input occurs.	Output occurs if inputs occur in a certain sequence.	Output occurs if input occurs under a specific condition.

2.2.2 Event Tree Analysis (ETA)

While a fault tree is devised to identify component failures that cause the top event to occur, an event tree begins with an initiating event, for instance, flammable liquid spill, and analyzes a sequence of actions and possible consequences based on the success or failure of such actions of barriers. Given the frequency of the initiating event, the event tree is able to generate the frequencies of each outcome by combining the probability of the barriers [66]. An example of the event tree of the liquid spill is taken from *Lee's Loss prevention in the process industries: Hazard identification, assessment and control* [67] and illustrated in Figure 4. Based on this event tree, a flammable liquid spill may lead to four different outcomes depending upon the types of situations following the spill. The numbers in the tree indicate conditional probabilities of such occurrences.

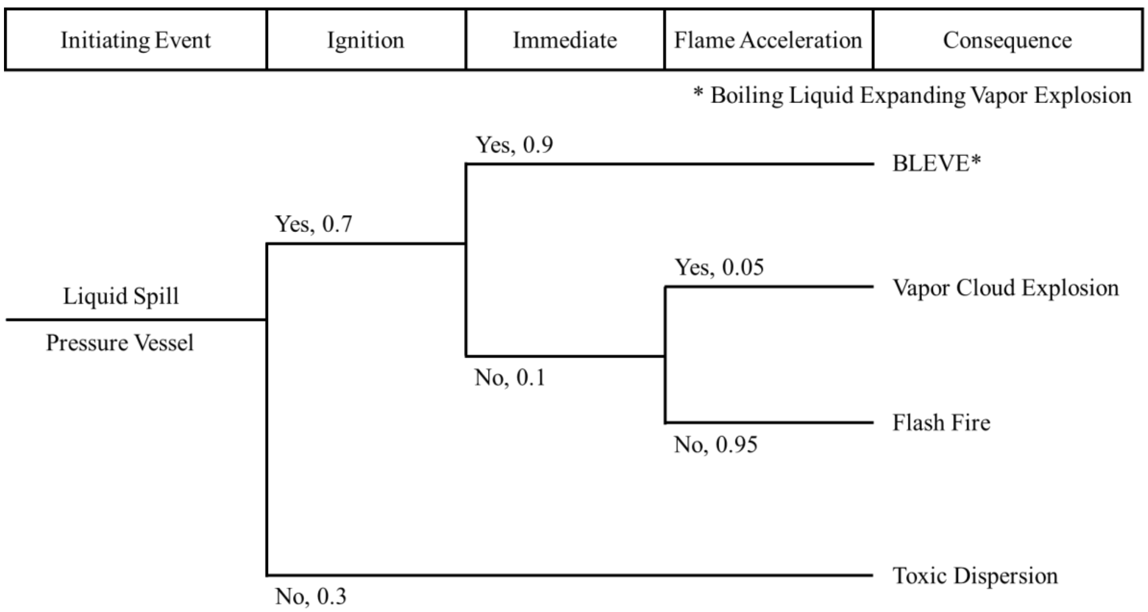


Figure 4. The Event Tree of Liquid Spill (Lee, 2012)

2.2.3 Bow-tie Analysis

In spite of aforementioned advantages, the fault tree analysis and the event tree analysis have limitations to some extent at which the overall risk scenarios cannot be described. Bow-tie (BT) analysis, which employs both a fault tree (FT) and an event tree (ET) at the same horizon, is very helpful to show the chain of events from causes of the fault tree to outcomes of the event tree. Having a fault tree rotated 90° clockwise on the left side and an event tree on the right side, the overall structure looks like a bow-tie after which the name of the analysis was taken [64]. The interface between the FT and the ET is made by making the top event of the FT the initiating event of the ET. Therefore, BT becomes able to represent the structure of the overall risk scenarios, which consist of primary events, intermediate events, the top event, safety barriers and consequences [68]. The schematic diagram of the bow-tie is provided in Figure 5. Safety barriers on the left are generally called preventive controls since they play as prevention measures while those on the right are termed as protective controls as they serve mitigation purposes [64].

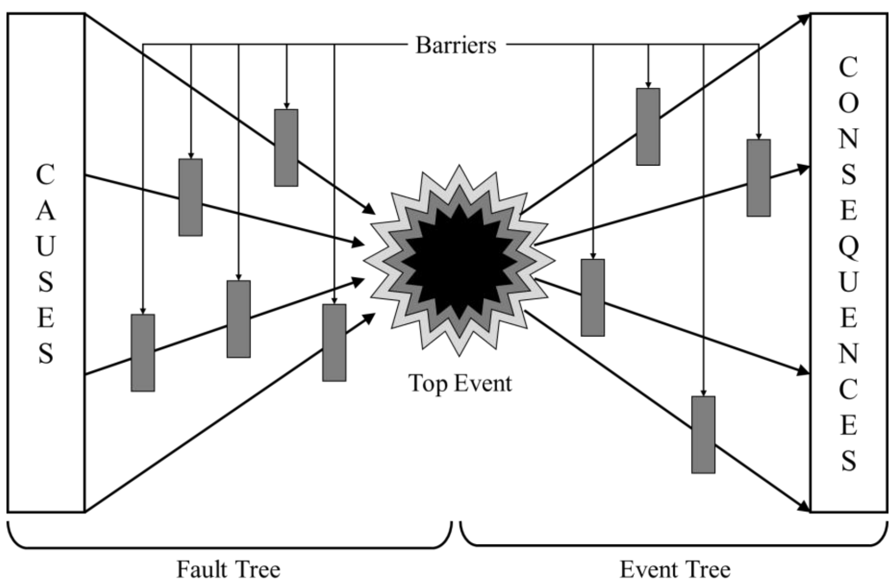


Figure 5. A Schematic Bow-tie Diagram

2.2.4 Hybrid Causal Logic (HCL) & Risk Influencing Factors (RIFs)

Basically, a risk model is a logical structure where relations among causes and consequences of incidents are depicted. Among many of them, Hybrid Causal Logic (HCL) [69] is employed for the BBN application in the present study. HCL is similar to Bow-tie model in that it connects a fault tree (FT) and an event tree (ET) but different in that it can accommodate multiple layers of variables that lie under the basic event of the fault tree and the safety barriers of the event tree. The HCL is designed to include both *hard* elements, which is deterministic, and *soft* attributes such as organizational and regulatory factors [70]. Initially, HCL methodology was developed and utilized for aviation industry [71] but its power of receiving various types of variables enables the applications to expand to the risk assessment of different industries such as offshore sectors [72]. A typical risk model using HCL is presented in Figure 6. Basically, this model consists of fault tree, event tree and Bayesian network. Some of the nodes in the Bayesian network called as Risk Influencing Factors (RIFs) [73] are connected to the basic events of fault trees to represent hidden causal factors underneath them. RIFs are defined as those factors that influence the level of risk of a system or an activity [73]. Employing RIFs in the risk model helps to identify and measure multiple dimensions that relate to managerial and organizational aspects. As a result, it becomes possible to draw a 'big picture' of the composite socio-technical risk profile.

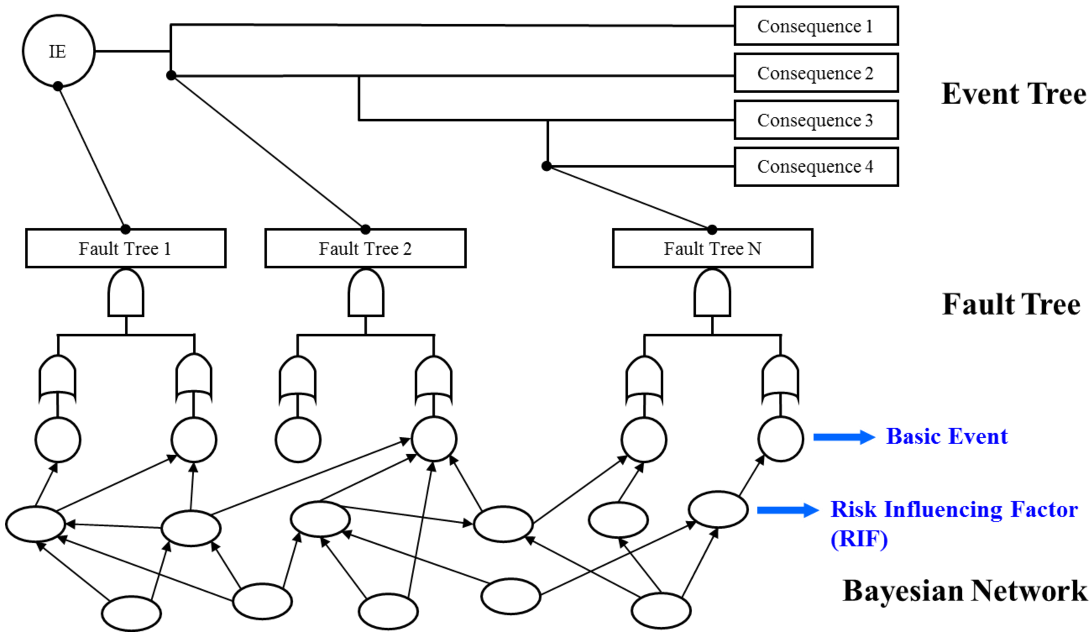


Figure 6. Risk Modelling Using Hybrid Causal Logic (Røed *et al.*, 2009)

Two levels of RIFs are employed in this study and presented in Figure 7. Level 1 and Level 2 RIFs are taken from Aven *et al.*'s BORA (Barrier and Operational Risk Analysis) [74] and Mannan *et al.*'s attributes of best-in-class safety culture [59], respectively. Since Level 1 RIFs are more superficial and formal elements that generally constitute safety management systems of an organization, they are placed above Level 2 RIFs in the risk model and thus impacted by them.

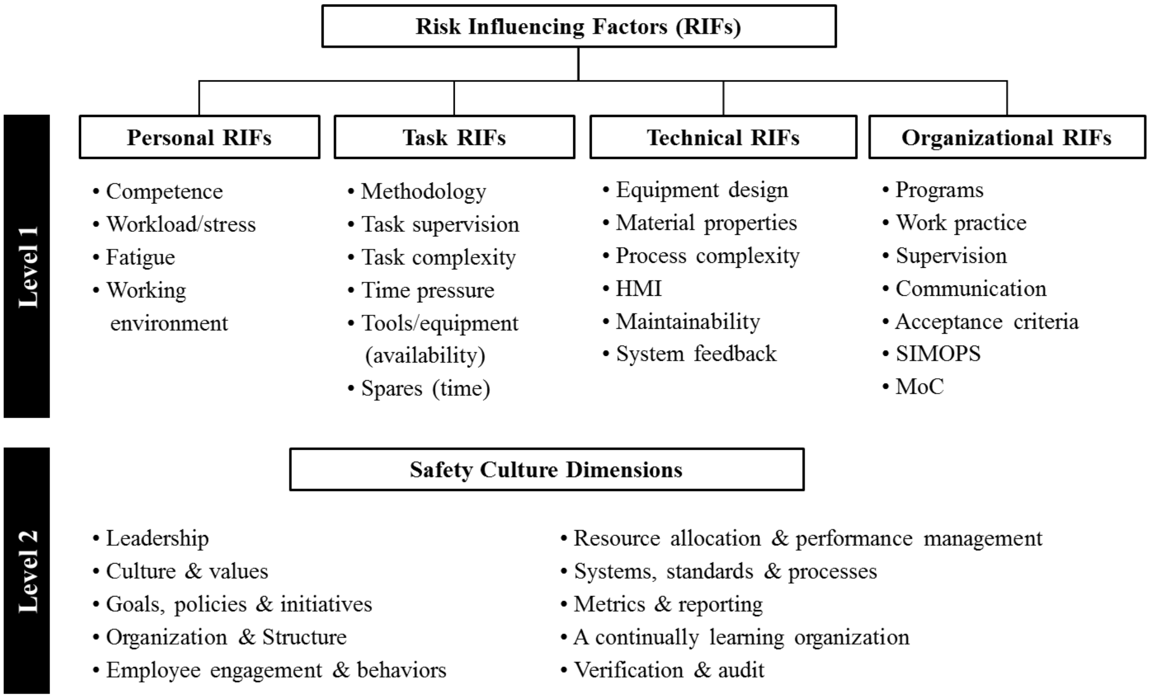


Figure 7. Two Levels of Risk Influencing Factors

2.3 Bayesian Belief Network (BBN)

There is a growing number of attempts to include human and organizational factors into conventional risk analyses where technical factors are generally accounted for. Because of the qualitative nature of such non-technical factors, a Bayesian Belief Network (BBN) or Bayesian Network (BN) is often utilized to incorporate new knowledge from observations or evidences, which are not only numerical data of technical components but also underlying Risk Influencing Factors, for example, the influence of safety culture.

2.3.1 Definition of the Bayes' Theorem

Named after the Reverend Thomas Bayes, a minister and a mathematician [75], Bayes' theorem, which provides mathematical grounds to a Bayesian Belief Network, is the statistical theorem that allows existing knowledge (A) to be updated from new observations or evidences (B) [64]. Because of the capability that factors in additional information, the Bayesian inference can be applied to medical and legal sectors, financial domains, safety and reliability analysis [76]. The basic Bayes' theorem for this update is shown in Eq. (2).

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \quad \text{Eq. (2)}$$

In order to explain the updating process, an example of the relationship between smoking and having a heart attack is presented in Figure 8.

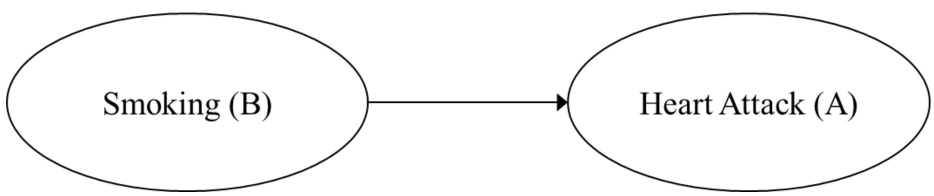


Figure 8. A Simple Bayesian Belief Network

Two random variables or nodes are connected with an arc to represent the direction of the relationship. Let's say that the prior probability of having heart attack, P(A) is 0.01, and the probability of a person being a smoker is 0.3, P(B)=0.3. Based on this initial *belief* and observed evidence or likelihood about smokers among those having cancer, *i.e.*, P(B|A)=0.7, the posterior probability of having cancer given the person is a smoker, P(A|B), can be calculated using Bayes' theorem.

$$P(A|B) = \frac{P(B|A) * P(A)}{P(B)} = \frac{0.7 * 0.01}{0.3} = 0.023$$

The calculation above shows that the posterior probability of having cancer becomes more than doubled by using the new evidence about smokers.

For discrete variables, Eq. (2) can be generalized into Eq. (3).

$$P(A_j|B) = \frac{P(B|A_j) * P(A_j)}{\sum_{i=1}^{k} P(B|A_i) * P(A_i)} \qquad \text{Eq. (3)}$$

where A and B_1, ..., B_k are events in a sample space Ω.

For continuous random variables X and Y, Bayes' theorem is expressed in terms of probability density function (*e.g.*, the pdf of a component) like shown in Eq. (4).

$$P(\lambda|\varepsilon) = \frac{L(\varepsilon|\lambda)f(\lambda)}{\int_0^\infty L(\varepsilon|\lambda)f(\lambda)d\lambda} \qquad \text{Eq. (4)}$$

where $f(\lambda)$ is the probability density function of a prior failure rate, λ, of a component and $L(\varepsilon)$ is the likelihood function based on a newly obtained evidence, ε. And then, $P(\lambda|\varepsilon)$ becomes the posterior pdf of λ given ε. Denominators, the total probability of the observed evidence, in both equations play as a normalizer that restricts the posterior probability between 0 and 1.

2.3.2 Definition of Bayesian Belief Network

Based on the Bayes' theorem, a Bayesian Belief Network (BBN) is a graphical model that represents random variables with a finite set of states and their conditional dependencies using a directed acyclic graph (DAG) and a set of node probability tables (NPTs). A BBN is a very powerful method for probabilistic reasoning [77]. The BBN provides a vehicle to perform numerical and traceable risk analyses and it makes possible to incorporate various types of data together. These data include, for example, equipment reliability data as well as soft data such as employee's competence and organizational change. BBN-based software such as AgenaRisk provides the following advantages [76]:

- Decision reasoning, *e.g.*, diagnostic and predictive, under uncertainty can be done.
- Actual and large-scale situations can be dealt with.
- A wide variety of data, *i.e.*, expert's judgment and empirical data can be blended.

Taking benefits of using BBN, several operational risk analyses that address those *soft* factors were conducted. Trucco *et al.* (2008) performed a BBN analysis for human and organizational factors (HOFs) using maritime guidelines and regulations [78]. The basic structure is built upon the Maritime Transportation System (MTS). The BBN modeling of HOFs is proven to be useful to figure out additional ways of reducing the risk at the organizational and regulatory perspectives [78]. Garcia-Herrero *et al.* (2013), on the other hand, demonstrate how to perform a BBN analysis for the relationship between safety culture and organizational culture in the context of nuclear industry [79]. Their work examines how to analyze the influence from organizational culture to safety culture using the Organizational Culture Inventory (OCI) [80]. They proposed as a result of research that the constructive style of organizational culture poses the strongest impact on the safety culture. An example of BBN modeling for process plants is also captured. Ale *et al.* (2014) develop a dynamic BBN model to represent risks with a real-time nature of a petroleum processing facility [81]. Not only are technical factors considered in that model, but also human factors and managerial actions are taken into account. The analyses show that management actions can play as a common cause failure [81].

Understanding the usefulness proven in the previous studies, this study attempts to demonstrate how evidences obtained from safety culture assessment can update the existing probabilities of events using a case scenario established upon a past chemical incident.

2.3.3 Illustrative Example of Bayesian Belief Network

Figure 9 shows a very simple Bayesian Belief Network based on the scenario originally provided by Poole and Neufeld [82] and the model is available in the AgenaRisk Version 6.2 [83]. The scenario describes a situation where a fire alarm goes off and, as a result, people leave the place and report to others. Basically, the fire alarm is activated by detecting fire but sometimes it is actuated by tampering. Six nodes are shown in this BBN to represent variables and their relationships are defined by the existence and the direction of arcs. A parent node is the one from which the arc departs and a child node is the one to which the arc arrives. Conditional probabilities given the state of the parent node are specified in NPTs. Some examples of the NPTs used in this case are provided in Table 7 and Table 8.

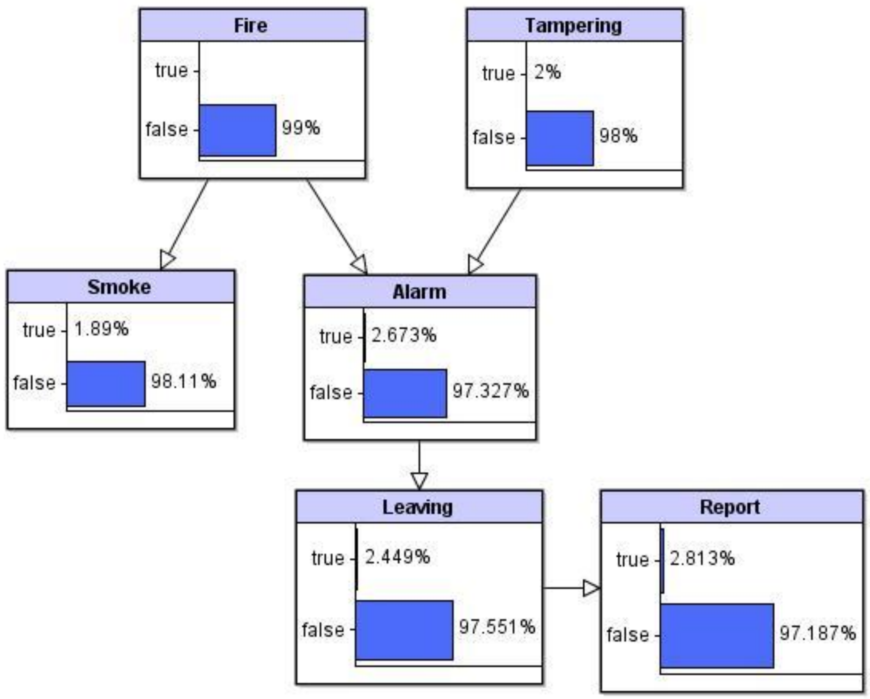


Figure 9. The Prior Probabilities in a Fire Scenario (AgenaRisk 6.2)

Table 7. The NPT for Smoke Node

Fire		True	False
Smoke	True	0.9	0.01
	False	0.1	0.99

Table 8. The NPT for Alarm Node

Tampering		True		False	
Fire		True	False	True	False
Alarm	True	0.5	0.85	0.99	0.0001
	False	0.5	0.15	0.01	0.9999

Table 7 shows that conditional probabilities of having smoke given the occurrence or non-occurrence of fire. If there is actual fire (true), the probability of observing smoke is 0.9 and that of not observing is 0.1. On the other hand, if the fire did not take place, the probability of observing smoke is as low as 0.01 and that of not having smoke is 0.99. Since the two states of the node are mutually exclusive and independent, the probabilities for those states sum up to 1 according to the Probability Axiom 2, which dictates that the sum of the probabilities in a sample space must be equal to 1. Table 8 shows the NPT in a case where two parent nodes exist. For instance, the probability of activating the true alarm given false tampering and true fire is as high as 0.99. However, if someone tampers the alarm and, at the same time, actual fire occurs, the probability of having true alarm is the same as that of having false one. Provided that NPTs are established for each of the nodes, the prior probabilities of having true alarm is obtained by marginalization as presented in Eq. (5).

$$
\begin{aligned}
P(AL = T) &= \sum P(AL = T|TM, FR) \\
&= P(AL = T|TM = T, FR = T) * P(TM = T) * P(FR = T) \\
&\quad + P(AL = T|TM = T, FR = F) * P(TM = T) * P(FR = F) \\
&\quad + P(AL = T|TM = F, FR = T) * P(TM = F) * P(FR = T) \\
&\quad + P(AL = T|TM = F, FR = F) * P(TM = F) * P(FR = F) \\
&= 0.02673
\end{aligned} \qquad \text{Eq. (5)}
$$

where AL is for alarm, TM for tampering, FR for fire, T for true and F for false.

According to the Probability Axiom 2, the probability of false alarm, P(AL=F) becomes 0.97327 (=1-0.02673). All the other prior probabilities can be calculated in this way and the results will be the same as shown in the Figure 9.

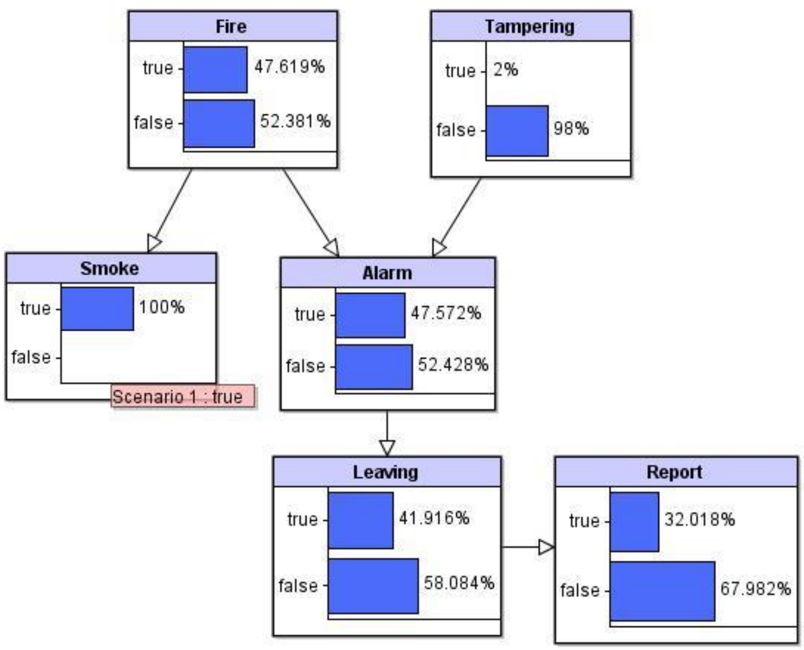


Figure 10. The Posterior Probabilities of a Fire Scenario

As introduced, the strength of a BBN is its power to update prior probabilities using new observations. For instance, the prior probabilities of alarm are updated by entering observations about smoke. When smoke is observed (smoke=true), the probability of true fire given true smoke is calculated using the Bayes' theorem as the following:

$$\mathrm{P(FR = T|SM = T)} = \frac{P(SM = T|FR = T) \times P(FR = T)}{P(SM = T)} = \frac{0.9 \times 0.01}{0.0189} = 0.47619 \qquad \text{Eq. (6)}$$

where SM stands for smoke.

When this updated probability of true fire is used for P(FR=T) and P(FR=F) in the Eq. (5), the posterior probability of true alarm is increased to 0.47572 as presented in Figure 10.

More details about principles and applications of Bayes' theorem and BBN can be found in a book written by Fenton and Neil [77].

3. METHODOLOGY

This study consists of the following steps to achieve the objectives stated in the earlier section: (1) proposing an approach to measure safety culture by looking through artifacts, (2) developing a Dimension Matrix to formulate binary combination of safety culture dimensions, (3) devising Grading Schemes to provide a list of choices that describe different degree of safety values, (4) Generating a safety culture assessment questionnaire based on the Dimension Matrix and Grading Schemes, (5) constructing a Bayesian Belief Network (BBN) using the case scenario and a risk model based on Hybrid Causal Logic (HCL) [72], (6) entering mock-up safety culture assessment data into Risk Influencing Factors (RIFs) in the BBN model, (7) performing various analyses, *e.g.*, diagnostic and predictive reasoning, using the BBN model, and finally (8) discussing analysis outcomes to examine how safety culture assessment results can be incorporated into the risk analysis of a process incident.

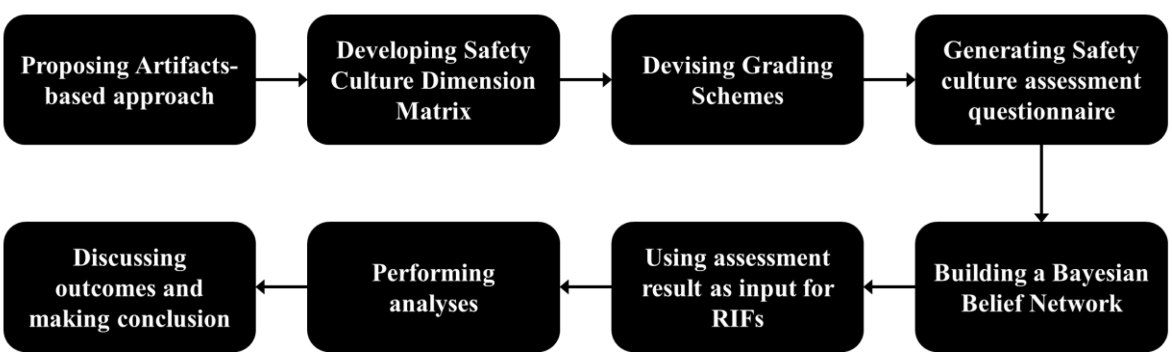


Figure 11. A Diagram of Research Steps

3.1 Artifacts-based Safety Culture Assessment

3.1.1 An Approach Looking through Artifacts

As mentioned before, safety culture is generally viewed as a subset of organizational culture. Therefore, the three levels of culture, artifacts, espoused values and underlying assumptions, developed by Schein (1990) [24], are employed in this study. The hierarchy of these levels of culture is displayed with an analogy of an iceberg in Figure 12. Artifacts are visible expressions that are observed in an organization. Included in these artifacts are, for example, safety sign, campaign, meeting agenda, employee’s behavior, Job Safety Analysis (JSA), organizational hierarchy, and the physical condition of equipment and facility. Espoused values represent values, beliefs and goals embraced by the organization. These values are identified in, for instance, mission/vision statement, safety slogan and long-term goals that are announced openly. Hence, Espousals are the public face and reputation of the company [84]. Lastly, deeply rooted are basic and underlying assumptions. The underlying assumptions, located at the bottom of member’s mentality, are beliefs that they take for granted. They are not articulated in a written form but members of an organization accept it as a ground for reasoning, deciding and acting.

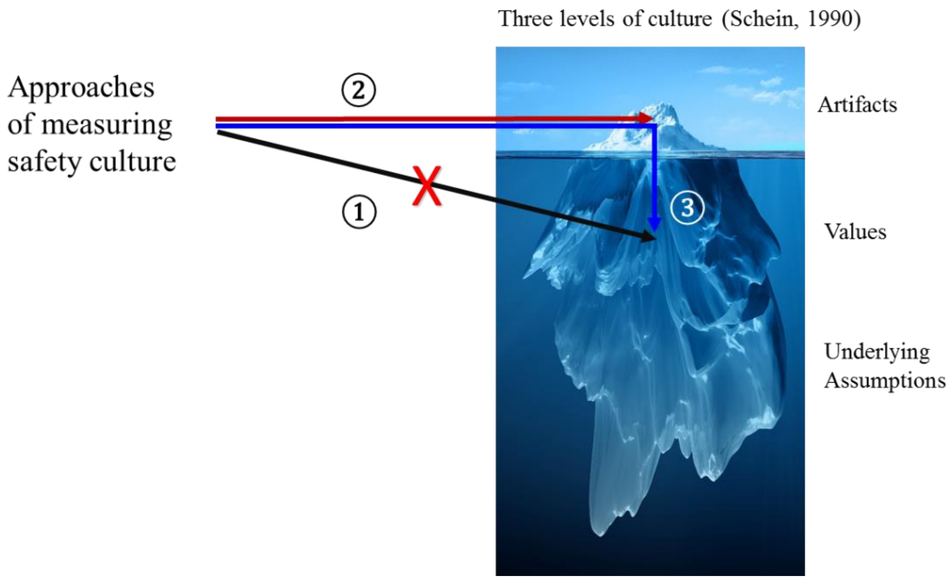


Figure 12. Three Levels of Culture and Three Approaches of Culture Measurement

Because safety culture possesses such tacit property that does not express itself in easily identifiable ways, it is generally known to be difficult to directly measure safety culture. This statement is illustrated as view ① in Figure 12. Instead, some researchers insist that safety climate, a part above the surface, can be measured since it refers to more observable and perceivable phenomena (view ②), *e.g.*, things on the work floor, and the employee's perception of safety attitude of his/her supervisor. Studies about safety climate have become abundant since Zohar (1980) published a research paper [38] that surveys perceived level of different aspects of safety climate in several industries. Due to the fact that it measures the perceived status of affairs, his study mostly deals with safety climate. The present study, however, suggests a framework that gauges the state of safety culture based on replies to questions which requires, in general, a higher level of comprehension of a company's 'how things are done around here'. Given the responses to the questionnaire is sincere, these would reveal more about the company's values (view ③). In other words, this study views how the level of safety culture can be determined from expressions and performance of safety practices and activities. For instance, a question in Figure 13 delineates an example of the approach suggested in this study.

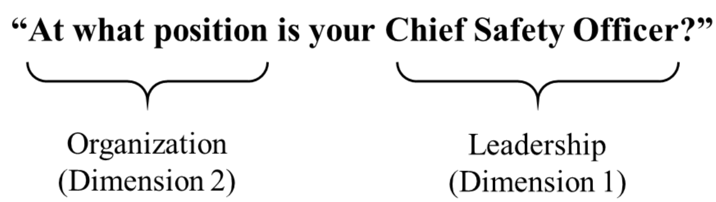


Figure 13. An Example of a Two-dimensional Question

Leadership of management is one of the most pivotal attributes that shape good or bad safety culture. This question asks the position of Chief Safety Officer (CSO) to find out how much values a company has for its safety leadership. An assumption made here is that the higher position the CSO takes, *e.g.*, CEO, the stronger its safety culture would be. In this case, the position of the CSO is a type of manifestation of managerial organizational structure and the difference in the position indicates the strength of safety culture in leadership.

Another finding from this question is that such question implies two different dimensions in its structure. In the question proposed in Figure 13, those dimensions are leadership and organization, respectively. Even though it is possible to make a question that includes more than two dimensions, this study suggests only binary combinations of safety culture dimensions. How to make those pairs is explained in the following section.

3.1.2 Safety Culture Dimension Matrix

Disassembling a question into binary dimensions requires a Safety Culture Dimension Matrix as presented in Figure 14. Ten characteristics of excellent safety culture proposed by Mannan *et al.* (2013) [59] are employed in this matrix. Accordingly, the matrix generates 45 cells where two different dimensions or characteristics intersect. For instance, when a question contains the characteristics of Leadership (LS) and Organization & Structure (OS), such pair is represented as LS-OS. And this pair is not differentiated from the reversely-ordered pair, *e.g.*, OS-LS. Therefore, the overall structure takes a right triangle. Abbreviations of those dimensions are included in the bracket after their names.

The matrix represents the structure of safety culture in an organization in a visual manner. Such structure visualization can be implemented by placing scores obtained through safety culture survey in those cells. Assigning different colors, for example, red for a score below 4, amber for 4 to 6, yellow for 6 to 8 and green for 8 to 10 can provide more graphical effect. In addition, this matrix provides guidance that helps to address safety culture dimensions evenly, and not to focus on particular aspects. As revealed through literature review in section 2.1.3, huge differences exist among survey tools in terms of the type of dimensions and the number of question items. However, this matrix provides all the combinations of two different dimensions with equal weights. A gray cell contains the sum of scores of both horizontal and vertical cells marked as blue arrows in the matrix. For instance, a total score of Organization & Structure (OS) is the sum of LS-OS, CV-OS, GP-OS, OS-EB, OS-RP, OS- SP, OS-MR, OS-LO and OS-VA. How scores are graded is discussed in the next section.

Leadership (LS)	1										
Culture & values (CV)	2	LS-CV									
Goals, policies & initiatives (GP)	3	LS-GP	CV-GP								
Organization & structure (OS)	4	LS-OS	CV-OS	GP-OS							
Employee engagement & behaviors (EB)	5	LS-EB	CV-EB	GP-EB	OS-EB						
Resource Allocation & performance management (RP)	6	LS-RP	CV-RP	GP-RP	OS-RP	EB-RP					
Systems, standards & processes (SP)	7	LS-SP	CV-SP	GP-SP	OS-SP	EB-SP	RP-SP				
Metrics & reporting (MR)	8	LS-MR	CV-MR	GP-MR	OS-MR	EB-MR	RP-MR	SP-MR			
A continually learning organization (LO)	9	LS-LO	CV-LO	GP-LO	OS-LO	EB-LO	RP-LO	SP-LO	MR-LO		
Verification & audit (VA)	10	LS-VA	CV-VA	GP-VA	OS-VA	EB-VA	RP-VA	SP-VA	MR-VA	LO-VA	
Dimension 2		1	2	3	4	5	6	7	8	9	10
	Dimension 1	Leadership	Culture & values	Goals, policies & initiatives	Organization & structure	Employee engagement & behaviors	Resource Allocation & performance management	Systems, standards & processes	Metrics & reporting	A continually learning organization	Verification & audit

A total score is the sum of its horizontal and vertical cells.

Figure 14. Safety Culture Dimension Matrix

3.1.3 Grading Scheme

How to make grades for such pairs generated in Safety Culture Dimension Matrix is one of the key conditions to achieve the purpose of this research. The method suggested in this study is called an *Artifacts-based* Grading Scheme, which is a list of different expressions of safety values that an organization possesses. For example, Table 9 is developed to answer the question in Figure 13 ("At what position is your Chief Safety Officer?"). While 5-point Likert Scale common in safety culture/climate surveys asks how much one agrees or disagrees about a given statement, this Grading Scheme offers plausible choices that manifest different level of safety culture. For quantification of the answer, different points are given to each of the choices. If the CEO serves as Chief Safety Officer, then 10 out of 10 points are assigned, for example. The lower position he/she takes, the lower points are given. In this study, the full mark is ten and the number of choices is either five or three depending on the granularity of differing answers.

Table 9. Management Level-based Grading Scheme

Choices		**Point**
(a)	CEO, Chief Executive Officer	10/10
(b)	COO, Chief Operating Officer	8/10
(c)	Vice President dedicated to safety	6/10
(d)	Vice President serving multiple duties	4/10
(e)	General manager or equivalent position	2/10

Descriptions in the Grading Scheme may vary upon the size and type of organizations. Nevertheless, this approach is assumed to provide a means where more stable answers can be acquired. Totally, 17 Grading Schemes are developed in this study. A list and details of those Artifacts-based Grading Schemes developed in this research are presented in Appendix A.

There are several benefits that can be taken from the methodology suggested above. First of all, safety culture can be measured in a comprehensive breadth by addressing all the cells in the Safety Culture Dimension Matrix. Second, visual or graphical representation of safety culture structure can also be displayed using the matrix. This matrix represents the overall structure of safety culture of an organization. Assigning different scores or colors, for example, will make such structure more visible. Third, it is assumed that more stable and objective measurement can be obtained by suggesting specific descriptions about safety culture items, instead of just asking employee's perception. Nonetheless, using artifacts are treacherous. Often times, they do not necessarily reveal the genuine state of affairs. Hence, being considerate and careful is necessary in designing a question and a Grading Scheme.

3.1.4 Safety Culture Assessment Questionnaire

One of the research objectives is to provide a set of questionnaires based on the aforementioned methodology. A questionnaire is composed of two dimensions, examples of questions and a Grading Scheme as presented in Figure 15. First of all, a pair of dimensions is selected from the Dimension Matrix. And then, a question that asks those two dimensions using one's knowledge and expertise is devised. Finally, one of the Grading Schemes is selected to appropriately answer the question.

Dimension 1	Dimension 2	Examples of Questions	Grading Scheme
Leadership	Leadership		Management Level-based
…	…		…
Verification & Audit	Verification & Audit		Fraction-based
One of ten Dimensions	One of ten Dimensions		One of 17 Schemes

Figure 15. A Structure of Safety Culture Assessment Questionnaire

In this study, a set of questionnaire is formulated based on my past experience and knowledge earned from literature [17, 36, 59]. The whole questionnaire based on this regime is provided in Appendix B.

3.2 BBN Application

As learned previously, Grading Schemes are devised as a way of translating qualitative states of affairs into numerical data that can be used in a risk analysis. Based on this, the BBN provides a platform on which different risk factors such as component failures and safety culture influences are connected each other. First of all, safety culture assessment results are transformed into ranks in Level 2 RIFs. And then, the relationship between Level 1 and 2 RIFs are determined by assigning different weights. The next step taking place between Level 2 RIFs and Safety Culture Influencing Factors (SCIFs) is called Q-Q transition where qualitative rankings are changed into probability distributions. Details of each step are denoted in the following sections.

3.2.1 Parameter Learning for RIFs

The survey results of safety culture assessment become an input for a BBN analysis. In order for safety culture assessment results to be taken into the BBN, a special function called parameter learning is utilized and it is simply executed in AgenaRisk. A parameter learning enables to learn population parameters from sample data [77]. A couple of assumptions are made for this function. Firstly, it is assumed that the population follows a normal distribution truncated (T-Normal) from 0 to 10 since the full mark for a safety culture dimension is equal to 10. Secondly, the prior mean and the variance of the population are uniform with equal probability over [0, 10] since both of them are unknown. Because the likelihood distribution is T-Normal and the prior one is assumed to be uniform, the posterior distribution, based on the combination of those two distributions, becomes T-Normal. By the way, in order to reduce the complexity of a Bayesian Network, only some of the RIFs are selectively chosen as in Table 10.

Table 10. RIFs Chosen for the Case Study

Level(no.)	RIFs
Level I (6)	Competence (personal), Procedure (task), HMI, Maintenance (technical), Work practice, Supervision (Organizational)
Level 2 (6)	Leadership, Organization & Structure, Employee engagement and behaviors, Resource allocation and performance management, Systems, standards and processes, Metrics and reporting

To simulate a company with higher safety culture, mock-up survey data for six periods, *i.e.*, months or quarters, are formulated in Table 11. Using Leadership scores for 6 periods from the table, parameters are learned and a ranked node of Leadership is earned as shown in Figure 16. This method is applied to the rest of mock-up survey data.

Table 11. Mock-up Safety Culture Assessment Data

Period	**1**	**2**	**3**	**4**	**5**	**6**
Leadership	8.5	9	8.7	8.0	8.2	8.6
Organization & structure	8.0	7.2	8.3	7.4	7.9	8.5
Employee engagement & behaviors	5.9	6.6	6.9	7.2	6.7	5.8
Resource allocation & performance management	7.4	6.5	6.4	5.9	6.2	5.7
Systems, standards & processes	7	7.4	7.8	8.1	8.2	8.0
Metrics & reporting	6.0	6.6	6.9	6.2	5.8	6.3

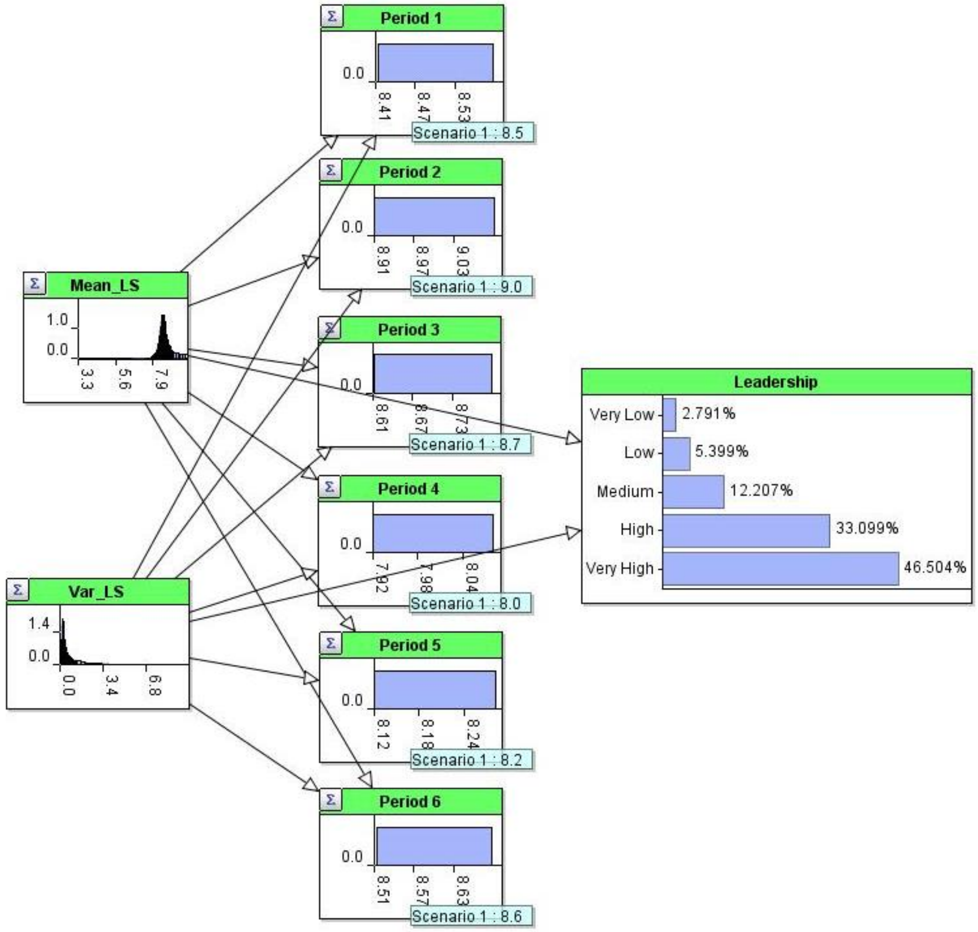


Figure 16. A Parameter Learning Using Leadership Scores

Table 12. Node Properties in a Parameter Learning

Node	Distribution type	Mean	Variance	Lower boundary	Upper boundary
Periods	T-Normal	Mean_LS	Var_LS	0	10
Mean_LS	Uniform	N/A	N/A	0	10
Var_LS	Uniform	N/A	N/A	0	10
Leadership	T-Normal	Mean_LS/10	Var_LS/10	0	1

Node properties of parameter learning are provided in Table 12. In order to match the scale of input from the Periods to that of Leadership node, it takes the mean and the variance divided by 10. Learned parameters for those six Safety Culture RIFs and their statistics summary are presented in Table 13. The percentage of each rank is determined by discretizing the continuous distribution resulting from the mean and variance nodes into the intervals. In this study, 5-point scale is employed to show finer differences in safety culture dimensions. 'Very low' represents the interval between 0 and 0.2 and 'Low' represents the interval between 0.2 and 0.4, etc.

Table 13. Statistics Summary of Level 2 RIFs

Level 2 RIFs	Mean	Std. Dev.	Ranks				
			Very low	Low	Medium	High	Very high
Leadership	0.73	0.21	2.79%	5.40%	12.21%	33.10%	46.50%
Organization & Structure	0.67	0.23	4.74%	8.92%	18.60%	34.39%	33.35%
Employee Engagement & Behavior	0.60	0.23	5.86%	13.16%	27.41%	33.44%	20.13%
Resource Allocation & Performance Mgmt	0.58	0.24	6.81%	14.66%	27.89%	31.48%	19.16%
Systems, Standards & Processes	0.67	0.22	3.96%	7.88%	18.28%	36.81%	33.08%
Metrics & Reporting	0.61	0.20	3.26%	10.14%	32.17%	39.58%	14.85%

3.2.2 Connecting RIFs Using Weighted Mean

The impact from the Level 2 RIFs to Level 1 RIFs is presented by weights placed on each of Level 2 RIFs. Determining the relationship – drawing an *arc* – between two levels of RIFs and assigning weights is recommended to be based on expert's judgment. Weights are given using a scale of 0 to 5 but the sum of the weights is made equal to 10. When it is assumed to be no dependency between two RIFs, no arc is drawn and a dash is filled in the cell instead of zero. The weights of Level 2 RIFs for Level 1 RIFs are listed in Table 14.

Table 14. The Weights of Level 2 RIFs for Level 1 RIFs

Weight	LS	OS	EB	RP	SP	MR	Sum
Maintenance	2	-	-	3	3	2	10
Supervision	2	3	2	-	-	3	10
Procedure	3	1	-	1	5	-	10
Competence	2	-	4	3	-	1	10
Work Practice	2	2	3	-	3	-	10
HMI	-	-	3	3	3	1	10

Note) LS=Leadership, OS=Organization & Structure, EB=Employee engagement & Behaviors, RP=Resource allocation & Performance management, SP=Systems, standards & Processes, MR=Metrics & Reporting.

3.2.3 Safety Culture Influencing Factors (SCIFs)

Once the connection between Level 1 and Level 2 RIFs is completed, bridging qualitative rankings, *e.g.*, very low to very high, of Level 2 RIFs to Safety Culture Influencing Factors (SCIFs) is imperative. SCIFs represent the effect of safety culture on the probabilities of events in the risk model. This transition is called qualitative-quantitative (Q-Q) transition [85].

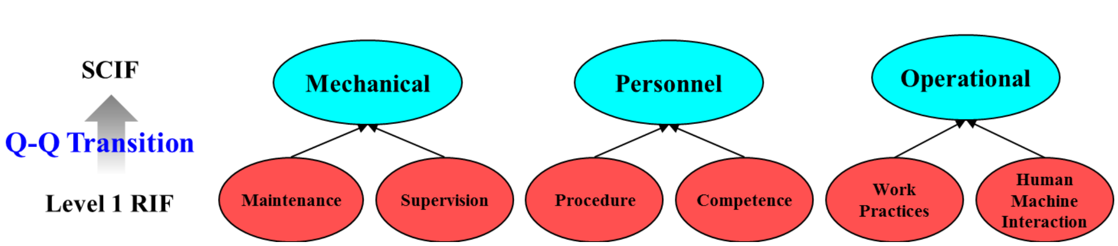


Figure 17. Q-Q Transition from Level 1 RIFs to SCIF

In this transition, Level 1 RIFs are parent nodes and SCIFs are child nodes. To make such transition take place, the node probability table (NPT) is established to provide conditional probability distribution (CPD) for the child node and its respective parents. Table 15 shows the conditional ranking of a child node, SCIF, given the ranks of its parents. For instance, Maintenance and Supervision nodes are parents of Mechanical SCIF. If Maintenance is low but Supervision is high, then Mechanical SCIF has a medium (I) rank based on the matrix below. And then, a T-Normal distribution of different parameters is assigned to each rank. T-Normal distribution is characterized by its mean and variance. When the variance is very large, a uniform distribution is formulated. On the other hand, when the mean is more or less than 0.5 and variance is close to 0, highly skewed distribution is obtained. Asking for expert's opinion for these parameters is also necessary to get more realistic posterior distribution. Parameters used in this transition are shown in Table 16.

Table 15. Conditional Ranking of a Child Node

	Very low	Low	Medium	High	Very high
Very low	Very Low (I)	Very low (II)	Low (I)	Low (II)	Medium (I)
Low	Very low (II)	Low (I)	Low (II)	Medium (I)	Medium (II)
Medium	Low (I)	Low (II)	Medium (I)	Medium (II)	High (I)
High	Low (II)	Medium (I)	Medium (II)	High (I)	High (II)
Very high	Medium (I)	Medium (II)	High (I)	High (II)	Very high

Table 16. Parameters of T-Normal for Each Rank

	Mean	Variance	Lower Boundary	Upper Boundary
Very high	0.1	0.1	0	1
High (II)	0.15	0.1	0	1
High (I)	0.35	0.1	0	3
Medium (II)	0.7	0.3	0	3
Medium (I)	1	0.3	0	5
Low (II)	1.5	1	0	5
Low (I)	3	1	0	10
Very low (II)	7	2	0	10
Very low (I)	10	3	0	10

Safety Culture Influencing Factors (SCIFs) would play as a change factor to generate a distribution of the predicted posterior probability based on the fixed prior probability and the ranks of its parents. In cases where two parents have both very low thus its child is assigned very low, the posterior probability is likely to increase by the factor of 10. Similarly, if the rank is determined very high, the posterior failure probability is likely to decrease by the factor of 0.1. However, when the conditional ranking turns out to be Medium (I), which is earned by two Medium parent nodes, the factor is equal to 1. That is, there is no significant change from the prior probability value. In order to keep the balance of such change effect, the product of opposite ranks, *e.g.*, Very low (I) and Very high or Low (I) and High (I), is designed to be equal to 1.

4. RESULTS

4.1 Case Scenario

4.1.1 Universal Form Clamp Incident

A case scenario for the application of BBN is established upon the CSB's investigation of Universal Form Clamp (UFC) incident [86]. This incident happened on June 14, 2006 at UFC's facility located in Bellwood, Illinois which manufactures several accessory products for concrete industry. While heating up a mixture of heptane and mineral spirits in a 2,200-gallon open-top tank equipped with steam coils, heated mixture was released from the tank and formed vapor cloud. The vapor cloud was ignited by an unknown ignition source several minutes later when a contractor deliver driver went into the facility while other workers working inside were evacuating. The contractor driver died several days later of severe burnt injury. The tank had a dual protection system to keep itself from being exposed to high temperature (High Temperature Protection System, HTPS): an automatic temperature control system (ATCS) and a manual temperature control system (MTCS). ATCS was composed of a temperature sensor and a pneumatic control unit to maneuver an automatic steam valve based on the measured temperature in the sensor. In addition to this, an operator was watching over the system by checking the temperature using an infrared thermometer and taking actions, *e.g.*, shutting down the manual valve when necessary.

Also, according to the CSB investigation [86], there were several safety barriers that would have prevented such incident from happening. The mixing room was designed to minimize the ignition sources based on the relevant standard. The adjacent area, however, was not designed to do so. Hence, it was likely for vapor cloud to move into the vicinity and get ignited. Other barriers identified in the investigation were sprinkler system and emergency evacuation. Sprinkler system would also have been able to reduce the potential of vapor cloud's ignition by wetting and cooling the flammable gas. Lastly, this case demonstrated that lack of emergency preparation for such a relatively huge release might lead to a fatality. If facility-wide emergency evacuation was effectively planned ahead and also regularly practiced, the life of the contractor driver could have been saved.

4.1.2 A Bayesian Risk Model for the Case Scenario

As the first step of building the Bayesian Risk Model, a fault tree and an event tree adapted from [87] are constructed as in Figure 18 and Figure 19, respectively. For the fault tree, two temperature control systems, ATCS and MTCS are considered as control barriers. The failure of ATCS is determined by three basic events: the failure of a sensor, a pneumatic control unit and an automatic valve. Likewise, the failure of MTCS is determined by other three basic events: the failure of an operator, an infrared thermometer and a manual valve. Three safety barriers are considered for the event tree in this case. They are ignition barrier, sprinkler system and emergency evacuation. Based on the success or failure of such safety or recovery barriers, four possible consequences are assumed: gas contained, wet vapor cloud, VCE with low fatality, and VCE with high fatality. The generic probabilities of these events presented in Table 17 are obtained from literature [87] and some of them are adapted to meet the risk modeling requirement, *i.e.*, that a probability must not exceed 0.1 as the maximum SCIF is as high as 10. In other words, when the prior probability is 0.15 and the SCIF is 10, for example, the posterior probability becomes 1.5, and this violates the Probability Axiom 2 that a probability of an event must not exceed 1.

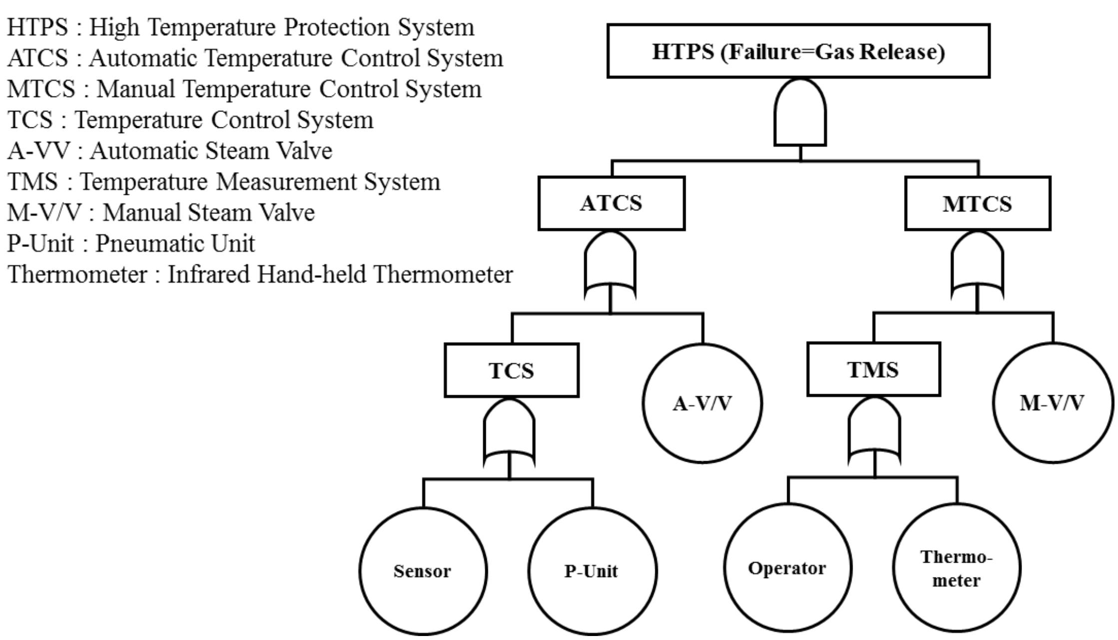


Figure 18. A Fault Tree of the High Temperature Protection System

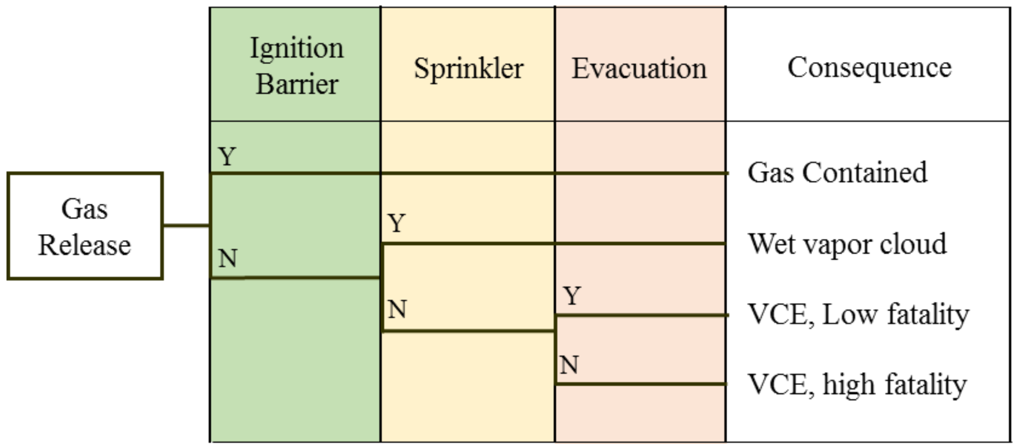


Figure 19. An Event Tree of the Gas Release

Table 17. Probability of Failure of Events

Event	Probability of Failure
Sensor	0.040
Pneumatic control unit	0.02015
Automatic steam valve	0.0276
Operator	0.100
Infrared thermometer	0.0468
Manual steam valve	0.0243
Ignition barrier	0.082
Sprinkler	0.040
Emergency Evacuation	0.100

In addition to the fault tree and the event tree, Level 1 RIFs and Level 2 RIFs are also incorporated into the risk model using AgenaRisk [77]. The overall structure of the risk model is presented in Figure 20. At the bottom of the Network, mock-up safety culture survey data are used to determine the percentage of each rank of Level 2 RIFs. And then, each of Level 1 RIFs is influenced by four Level 2 RIFs. Connection between Level 1 RIFs and Level 2 RIFs is achieved by placing different weight on each of Level 2 RIFs influencing a Level 1 RIF. The details of such weight placement are described in Section3.2.2. And then, two Level 1 RIFs are connected to one Safety Culture Influencing Factor (SCIF). Three SCIFs are introduced in this model: Mechanical, Personnel and Operational SCIFs. The naming and concept of these SCIFs are obtained from Pasman *et al*.'s work [88]. The SCIF plays as a change factor to represent the impact of safety culture that leads to basic events of the fault tree and safety barriers of the event tree. It also allows the transition from qualitative rankings to quantitative distributions, which is called Q-Q transition. Wang and Mosleh (2010) propose the QQBBN (Qualitative-Quantitative Bayesian Belief Networks) and demonstrate such transition method in a simple case [85]. However, the present work exhibits its application to a more complicated network in which deeper organizational factors are addressed. The propagation from the basic events to the final consequences follows the logic gates – *AND* or *OR*– in the fault tree, and the pathways – *Success* or *Failure* – in the event tree.

Again, the overall risk model presented Figure 20 enables to combine not only technical factors but also soft factors such as safety management and organizational elements. This model is expected to provide advantages that allow various analyses to be performed and the results of such analyses are provided in the following section.

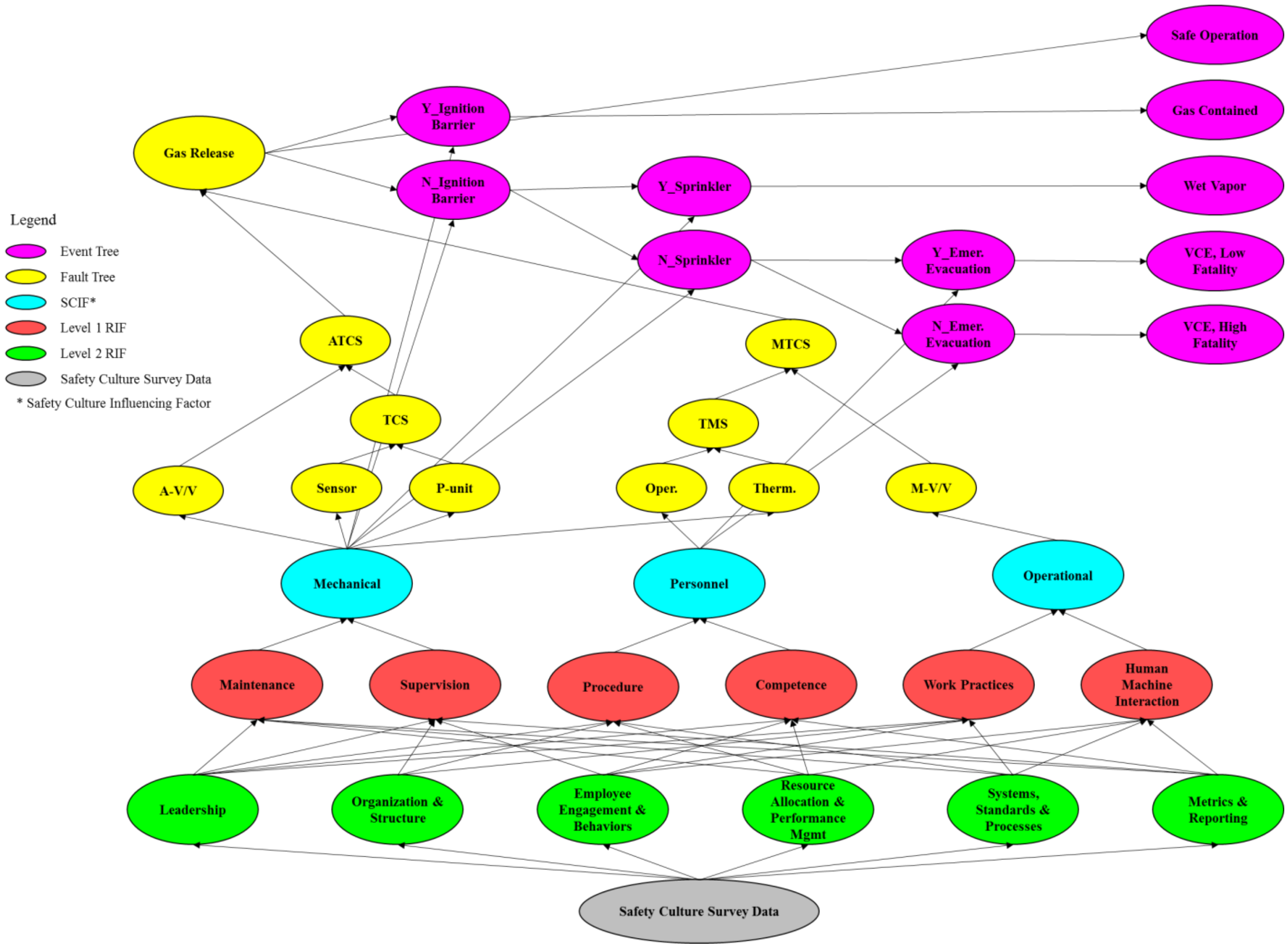


Figure 20. The Bayesian Risk Model for the Case Scenario

4.2 BBN Results

Using the methodology explained previously and the scenario built upon the incident case, a BBN model where both technical and organizational factors are combined is established. AgenaRisk [77] provides very useful functions to enable different analyses such as predictive and diagnostic reasoning. First of all, prior generic values of probability of failure are updated based on new evidences which are represented by SCIFs. As a result, posterior probability distributions are obtained for the events in the fault tree and the event tree. Based on this baseline case, several analyses are performed to figure out, *e.g.*, which Risk Influencing Factors (RIFs) make the most contribution to achieving a certain probability of an event (diagnostic reasoning), and to find out how worsened safety culture affects the probabilities of consequences. The BBN results of fault tree and event tree are provided as intermediate outcomes.

4.2.1 Results for the Fault Tree

With the inclusion of Risk Influencing Factors (RIFs) and Safety Culture Influencing Factors (SCIFs), the posterior failure probabilities of the fault tree are estimated. The posterior probabilities are updated from prior generic data, single point estimate of failure rate, by including RIFs and SCIFs. The BBN results of two intermediate scenarios, the failure of Automatic Temperature Control System (ATCS) and that of Manual Temperature Control System (MTCS), are presented in Figure 23 and Figure 24, respectively. As all the three basic events are associated with mechanical integrity, only Mechanical SCIF is connected to them. However, for the scenario of

MTCS failure, each of three SCIFs is used for each basic event. For example, Personnel SCIF is connected to Operator failure, Mechanical SCIF for Thermometer and Operational SCIF for Manual Steam Valve. The BBN result for the overall fault tree is shown in Figure 25.

The BBN results reveal that the posterior distribution turns out to be right-skewed thus has a long tail towards the right side which represents rarely expected high probabilities due to uncertainty involved in Low or Very low status of SCIFs. Simple examples of such skewed distributions are presented in Figure 21 and Figure 22.

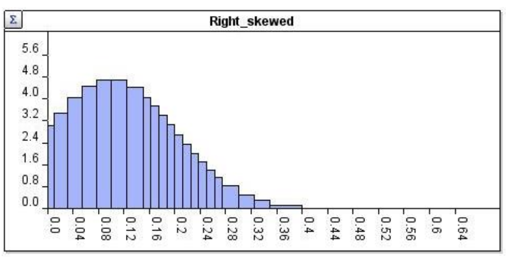


Figure 21. Right-skewed Distribution

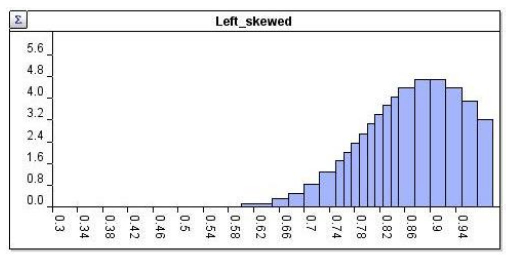


Figure 22. Left-skewed Distribution

The comparison between prior generic single point value and posterior probability data for the intermediate events and the top event are presented in Table 18. Values of the posterior probability distribution are obtained from Figure 25. Mean values are similar to or slightly larger than the generic values due to the tails of probability distributions but all the median values are found to be less than the generic data. This is explained by the existence of Very low and Low ranks of safety culture nodes. Even though their percentages are quite small, they represent rare conditions where safety culture is severely weakened.

Table 18. The Comparison between Generic and Posterior Probability in FT

Event	Generic Probability	Posterior Probability Distribution				
		Mean	Median	Std. Dev.	25^{th} Percentile	75^{th} Percentile
ACTS	0.085	0.093	0.071	0.090	0.039	0.119
MCTS	0.163	0.159	0.132	0.130	0.076	0.200
HTPS	0.014	0.020	0.008	0.046	0.003	0.019

Figure 23. The BBN Result of the Failure of ATCS

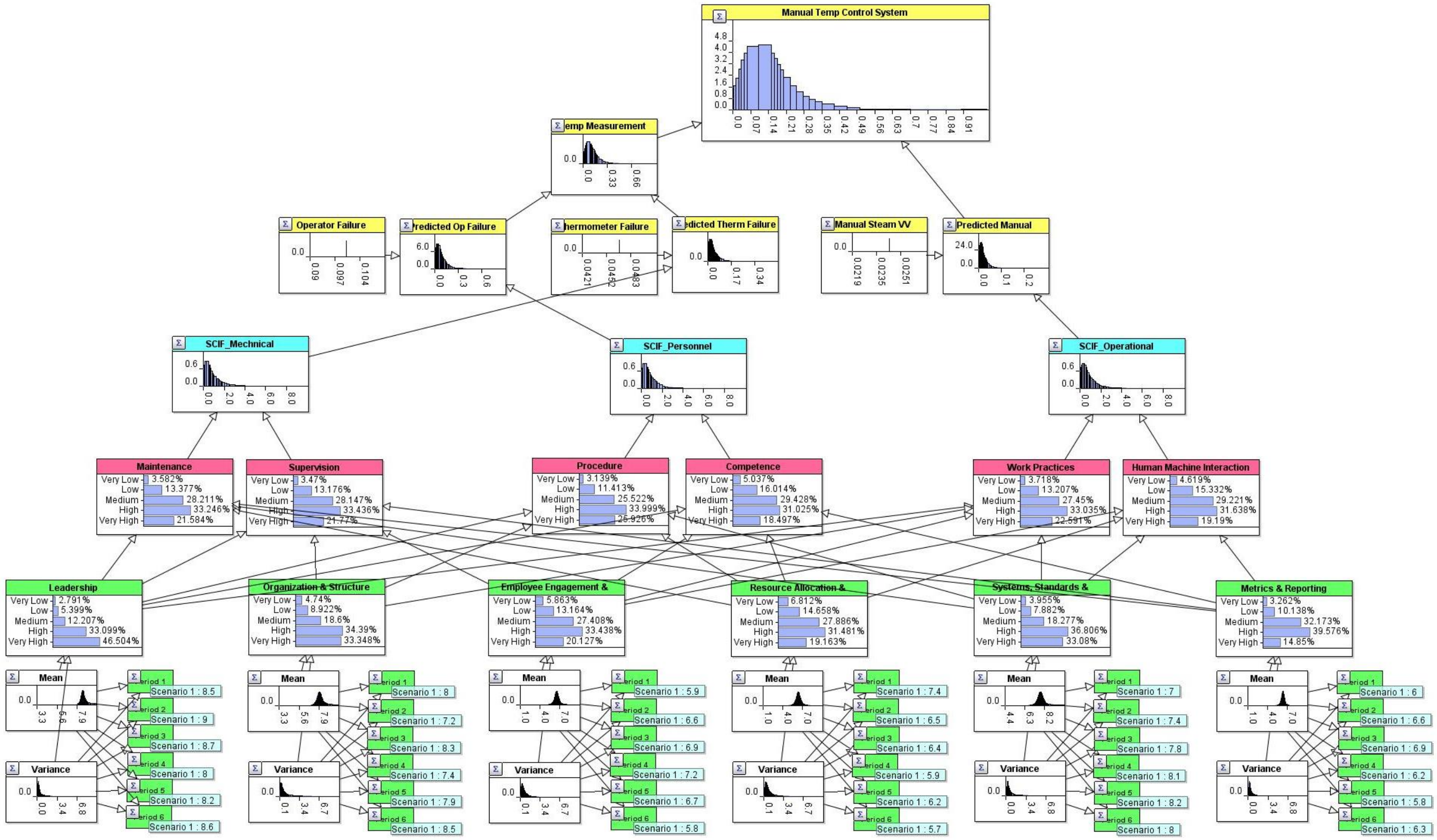


Figure 24. The BBN Result of the Failure of MTCS

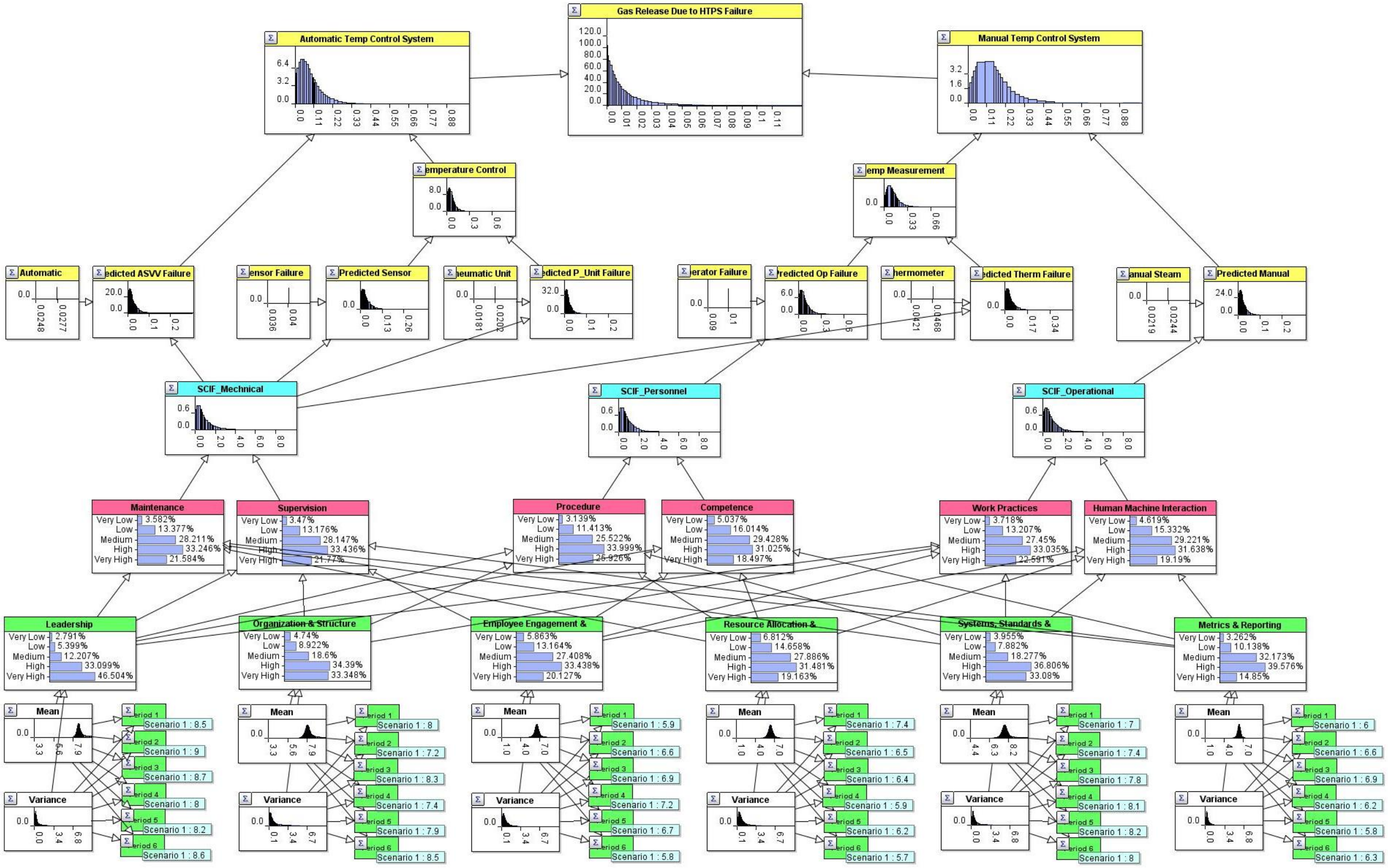


Figure 25. The BBN Result of the Overall FT

Based on this overall baseline FT model, a predictive reasoning is carried out to figure out the difference from a medium level of safety culture. The BBN diagram is shown in Figure 26 and the comparison results are presented in Table 19. To reduce the complexity of the overall BBN model and to facilitate the comparison between different states, percentages of ranks earned from parameter learning in the Section 3.2.1 are manually entered in each of Level 2 RIFs. The case of higher level safety culture is shown in blue and that of medium level in green in the diagram. The higher level is represented by the mock-up safety culture survey data presented earlier in Table 11. The medium level of safety culture is instantiated by setting the rank as medium for all the Level 2 RIFs. The results show that the mean probability of ATCS and MTCS increases from 0.093 to 0.134 (44%) and 0.159 to 0.246 (55%), respectively when medium level of safety culture is considered. And also, the mean probability of the top event, HTPS, increases from 0.020 to 0.045 (125%) when medium level of safety culture is supposed.

In addition, a diagnostic inference is performed to understand which safety culture dimensions need improvement to achieve a certain target probability. To compare with the baseline case, the target probability of 0.001 is assigned to the top event, gas release, of the fault tree. Typical risk criteria employed by petro-chemical industry suggest probability of such event between 1E-4 and 1E-5 as tolerable [89]. Nevertheless, considering that the probability of the top event calculated from prior generic failure data is as high as 0.0139, the target value of 0.001 is deemed as an attainable goal only with the improvement of safety culture, not relying on any additional technical barriers. The BBN graph for this comparison is presented in Figure

27. In that graph, blue bars represent the baseline case and orange ones indicate the target state. The comparison results are presented in Table 20 and they show that, in order to reach such target, significant improvement is required in Maintenance and Supervision for Level 1 RIF and Leadership and Systems, Standards & Processes for Level 2 RIF. To indicate the relative degree of change between the baseline case and the target state, the following calculation is performed:

$$\text{Relative Change} = \frac{Target\ state - Baseline\ case}{Baseline\ case} \times 100(\%) \qquad \text{Eq. (7)}$$

The determination of the most influential factors in these comparisons is based on the sum of the absolute values of ‘Very low + Low’ and ‘High + Very high’.

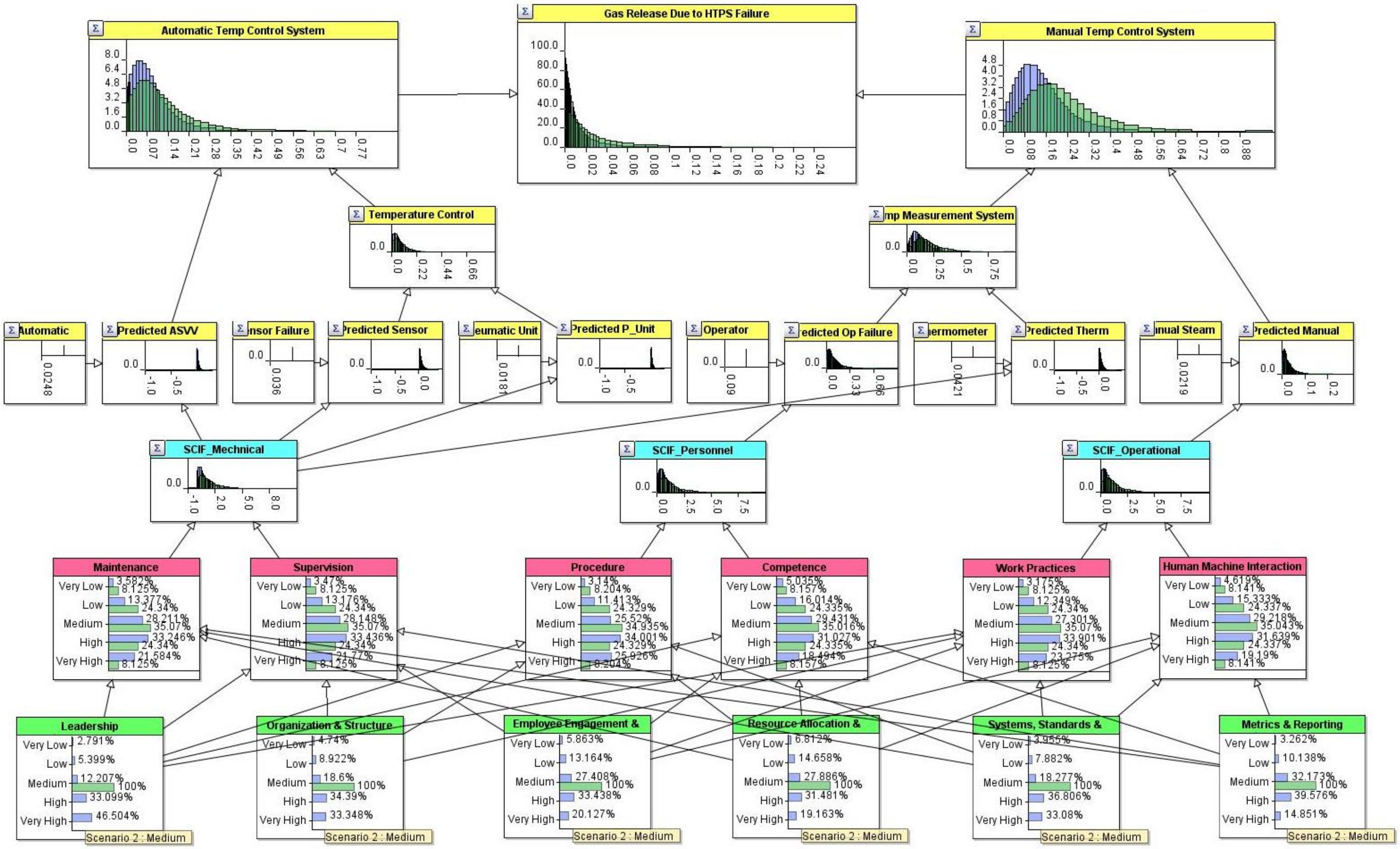


Figure 26. A Predictive Reasoning for FT Given Medium Safety Culture

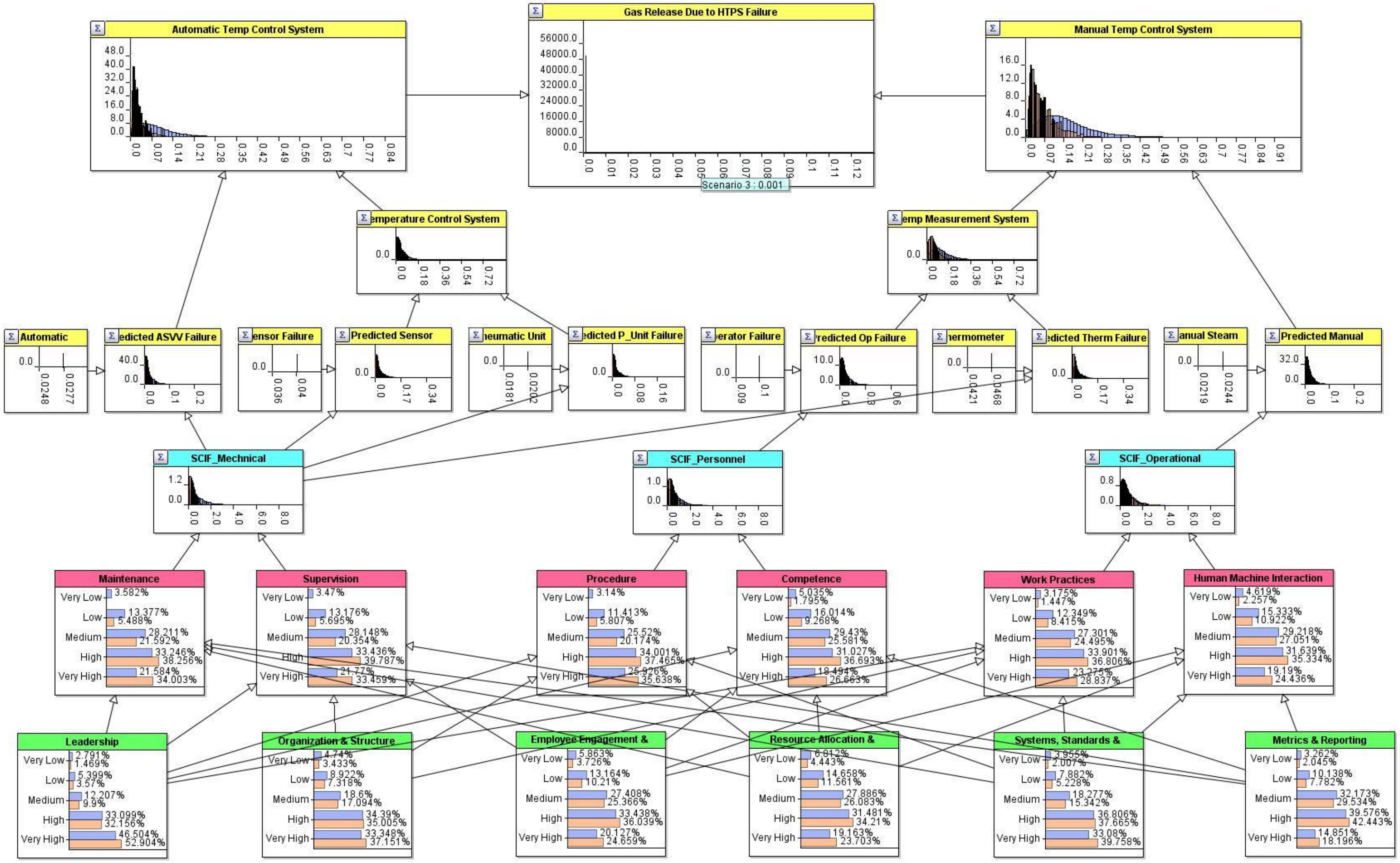


Figure 27. A Diagnostic Reasoning for FT Given Target Probability

Table 19. The Differences between Higher and Medium Level of Safety Culture

Event	Higher Level (Baseline)			Medium Level		
	Mean	Median	Std. Dev.	Mean	Median	Std. Dev.
ATCS	0.093	0.071	0.090	0.134	0.100	0.120
MTCS	0.159	0.132	0.130	0.246	0.207	0.169
HTPS	0.020	0.008	0.046	0.045	0.023	0.064

Table 20. The Differences between the Baseline Case and the Target State

RIFs		Very low + Low		Medium		High + Very high	
		Baseline	Target	Baseline	Target	Baseline	Target
		Relative Change		Relative Change		Relative Change	
Level 1	Maintenance	17.0%	6.1%	28.2%	21.6%	54.8%	72.3%
		-63.7%		-23.5%		31.8%	
	Supervision	16.6%	6.4%	28.1%	20.4%	55.2%	73.2%
		-61.6%		-27.7%		32.7%	
	Procedure	14.6%	6.7%	25.5%	20.2%	59.9%	73.1%
		-53.8%		-20.9%		22.0%	
	Competence	21.0%	11.1%	29.4%	25.6%	49.5%	63.4%
		-47.4%		-13.1%		27.9%	
	Work Practices	15.5%	9.9%	27.3%	24.5%	57.2%	65.6%
		-36.5%		-10.3%		14.8%	
	HMI	20.0%	13.2%	29.2%	27.1%	50.8%	59.8%
		-33.9%		-7.4%		17.6%	
Level 2	Leadership	8.2%	5.0%	12.2%	9.9%	79.6%	85.1%
		-38.5%		-18.9%		6.9%	
	Organization & Structure	13.7%	10.8%	18.6%	17.1%	67.7%	72.2%
		-21.3%		-8.1%		6.5%	
	Employee Engagement & Behavior	19.0%	13.9%	27.4%	25.4%	53.6%	60.7%
		-26.8%		-7.5%		13.3%	
	Resource Allocation & Performance Mgmt	21.5%	16.0%	27.9%	26.1%	50.6%	57.9%
		-25.5%		-6.5%		14.4%	
	Systems, Standards & Processes	11.8%	7.2%	18.3%	15.3%	69.9%	77.4%
		-38.9%		-16.1%		10.8%	
	Metrics & Reporting	13.4%	9.8%	32.2%	29.5%	54.4%	60.6%
		-26.7%		-8.2%		11.4%	

4.2.2 Results for the Event Tree

As learned throughout this work, safety culture influences not only basic events of a fault tree but also it affects the safety barriers or recovery barriers of an event tree. This section illustrates how the consequences of an initiating event are impacted by safety culture via SCIFs. The top event of the fault tree, gas release due to HTPS failure, is used as an initiating event of the event tree. Similar to what is done in the fault tree, SCIFs are connected to the safety barriers, for instance, Mechanical SCIF for Ignition Barrier and Sprinkler nodes and Personnel SCIF for Emergency Evacuation node. The BBN result for the overall ET is presented in Figure 28. The predicted posterior probabilities of final consequences are compared with the calculation outcomes using generic probability data, which is presented in Table 21. Similar to the results of FT, mean values of posterior probabilities are larger than the calculated values of generic data due to a long tail.

Table 21. The Comparison between Generic and Posterior Probability in ET

Consequence	Calculation from Generic Probability	Posterior Probability Distribution				
		Mean	Median	Std. Dev.	25^{th} Percentile	75^{th} Percentile
Safe Operation	0.986	0.981	0.992	0.002	0.981	0.997
Gas Contained	1.28E-2	1.48E-2	7.75E-3	2.27E-2	3.04E-3	1.74E-2
Wet Vapor	1.09E-3	3.45E-3	3.46E-4	1.58E-2	7.70E-5	1.52E-3
VCE, Low Fatality	4.10E-5	7.93E-4	7.38E-6	7.05E-3	8.67E-7	6.35E-5
VCE, High Fatality	4.56E-6	2.91E-4	4.65E-7	8.98E-3	3.94E-8	5.31E-6

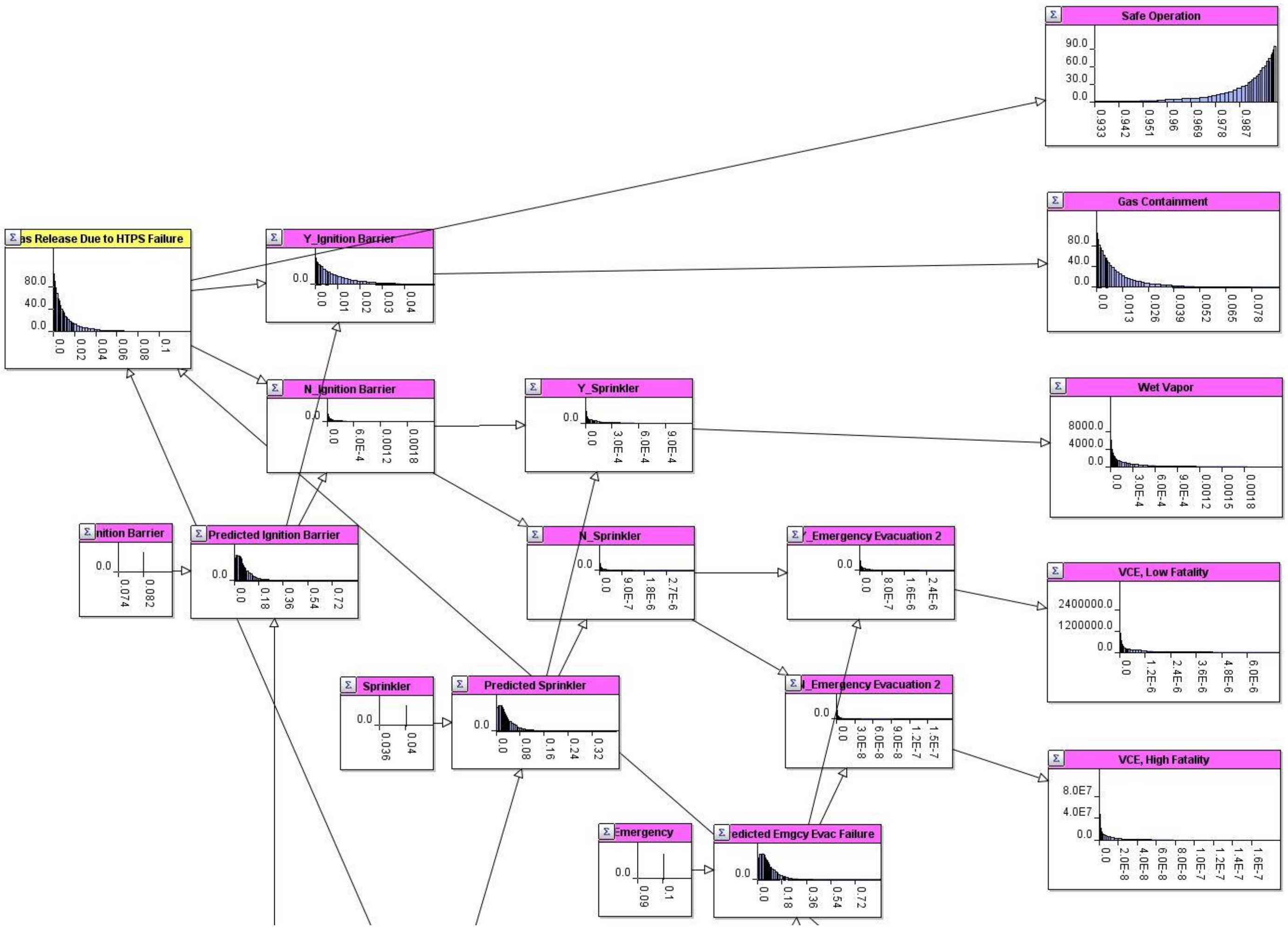


Figure 28. The BBN Result of the Overall ET

4.2.3 Results for the Overall Risk Model

By assembling the FT and the ET, the BBN of the overall risk model is developed and presented in Figure 31. The overall structure of the BBN is quite similar to that of the HCL-based risk model drawn in Figure 6. Based on these baseline results, a diagnostic analysis is performed by assigning a specific target probability to one of the consequences, *e.g.*, 0.99999 for Safe Operation (or 1E-5 for any unsafe occasions). The diagram for this analysis is presented in Figure 32. The analysis results are shown in Table 22 and the differences of only Level 2 RIFs are provided to figure out which elements of safety culture need improvement. Using Eq. (7), a comparison between baseline case and Safe Operation state is made similarly as what has been done in Table 20. Based on the results, Leadership and Systems, Standards & Processes require such improvement effort to the most extent.

Table 22. The Differences between States for Safe Operation

Level 2 RIFs	Very low + Low		Medium		High + Very high	
	Baseline	Safe Operation	Baseline	Safe Operation	Baseline	Safe Operation
	Relative Change		Relative Change		Relative Change	
Leadership	8.2%	5.9%	12.2%	10.6%	79.6%	83.5%
	-28.5%		-12.8%		4.9%	
Organization & Structure	13.7%	11.6%	18.6%	17.6%	67.7%	70.8%
	-15.1%		-5.5%		4.6%	
Employee Engagement & Behavior	19.0%	15.7%	27.4%	26.3%	53.6%	58.0%
	-17.3%		-4.1%		8.3%	

Table 22 Continued

Level 2 RIFs	Very low + Low		Medium		High + Very high	
	Baseline	Safe Operation	Baseline	Safe Operation	Baseline	Safe Operation
	Relative Change		Relative Change		Relative Change	
Resource Allocation & Performance Mgmt	21.5%	17.8%	27.9%	26.9%	50.6%	55.3%
	-17.1%		-3.7%		9.3%	
Systems, Standards & Processes	11.8%	8.7%	18.3%	16.5%	69.9%	74.9%
	-26.9%		-9.8%		7.1%	
Metrics & Reporting	13.4%	10.8%	32.2%	30.4%	54.4%	58.8%
	-19.5%		-5.4%		8.0%	

Figure 33 depicts how the baseline case changes if some dimensions of safety culture get worse. To simulate an economic downturn in which safety leadership and resources for safety may compromise, both Leadership and Resource Allocation & Performance Management are instantiated to be Very low as presented in Figure 29 and Figure 30 while other dimensions remain unchanged. Because of the weakened safety culture, the probabilities of consequences are changed and the results are presented in Table 23. Particularly, the probabilities of vapor cloud explosion (VCE) with low and high fatality are increased by the factor of 4 and 5, respectively.

Table 23. The Differences between States Due to Worsened Safety Culture

Consequence	Baseline Case		Worsened Safety Culture	
	Mean	Std. Dev.	Mean	Std. Dev.
Safety Operation	0.981	0.002	0.937	0.009
Gas Contained	1.48E-2	2.27E-2	4.33E-2	4.14E-2
Wet Vapor	3.45E-3	1.58E-2	1.72E-2	3.93E-2
VCE, Low Fatality	7.93E-4	7.05E-3	4.06E-3	1.40E-2
VCE, High Fatality	2.91E-4	8.98E-3	1.91E-3	1.02E-2

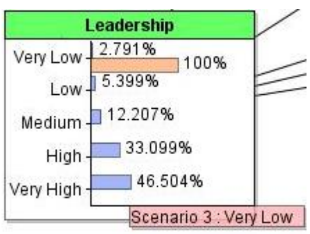


Figure 29. Worsened Leadership

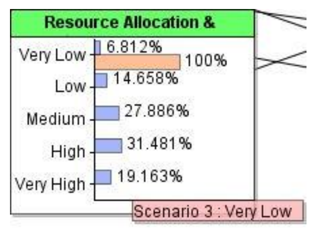


Figure 30. Worsened Resource Allocation & Performance Mgmt

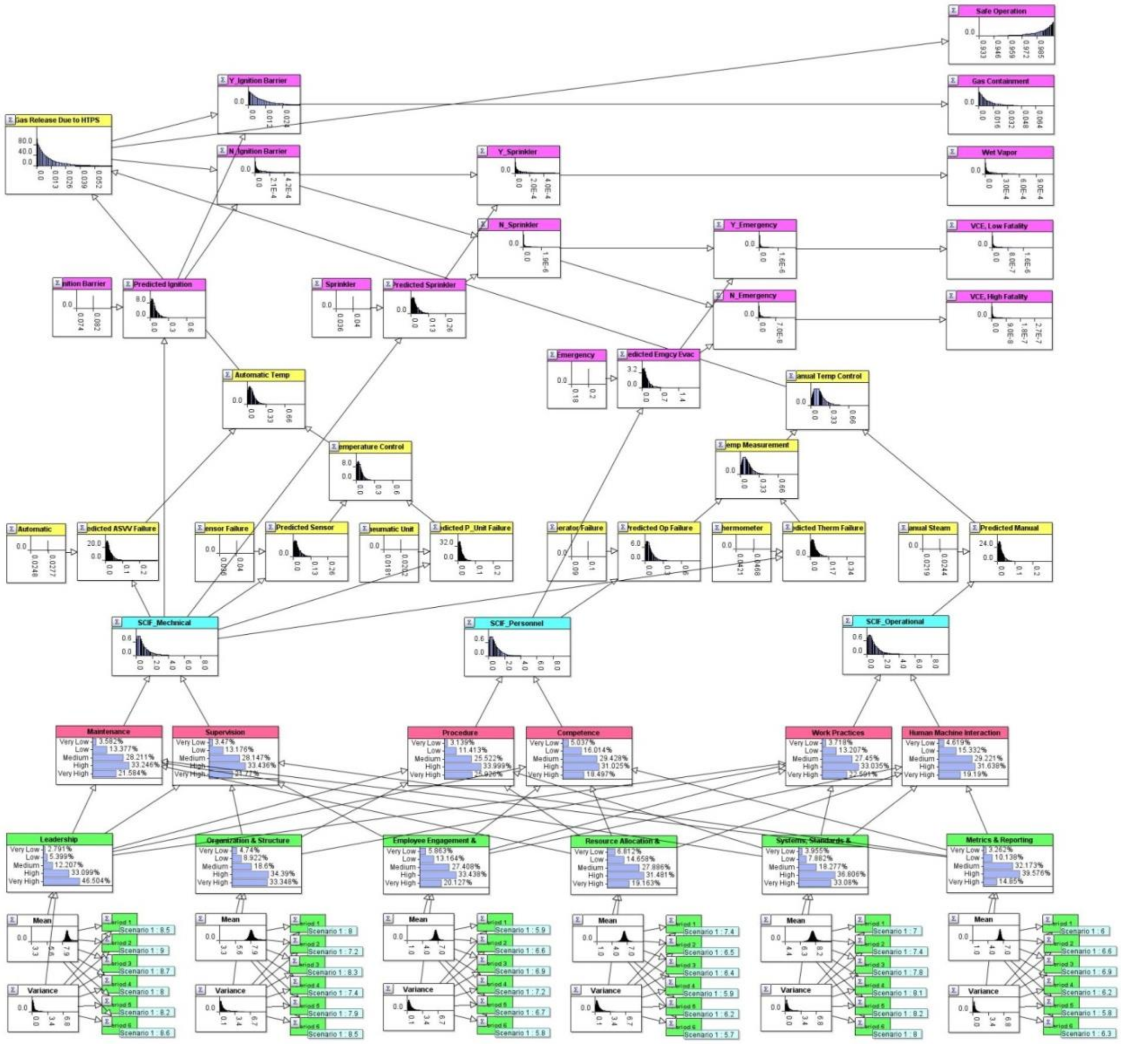


Figure 31. The Baseline BBN Result of the Overall Risk Model

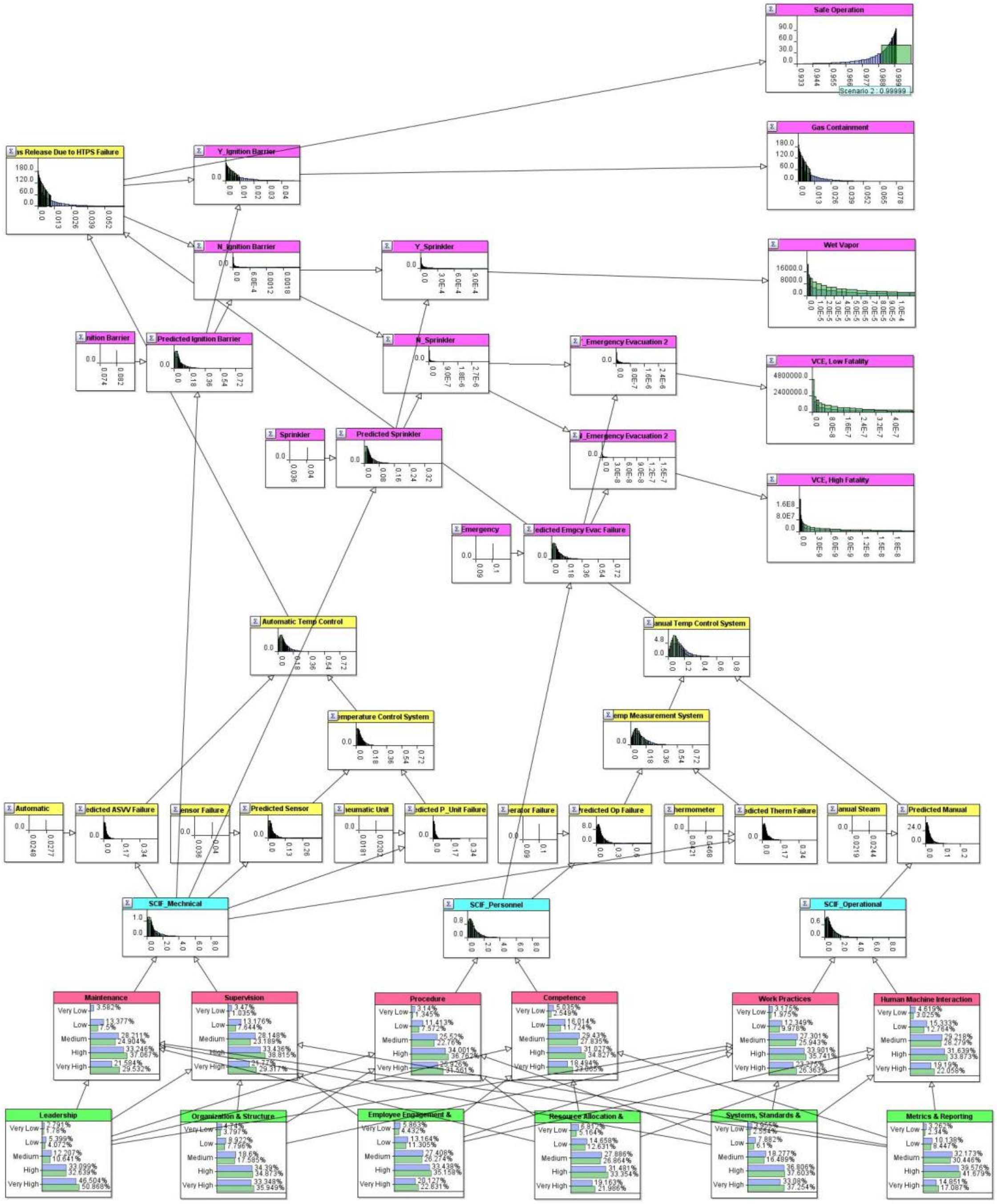


Figure 32. A Diagnostic Reasoning for Safe Operation

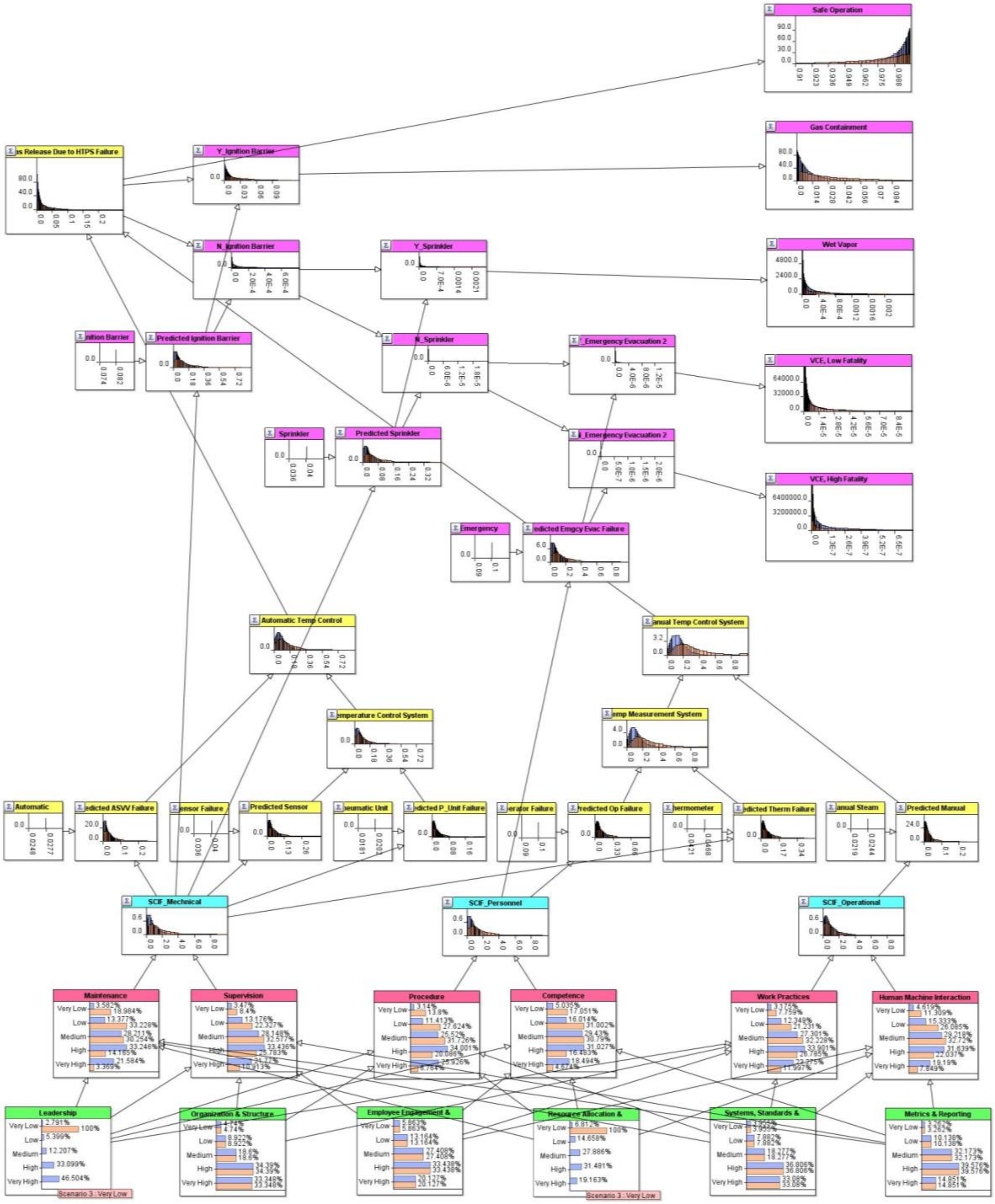


Figure 33. A Predictive Reasoning for Worsened Leadership & Resource Allocation

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Safety culture is increasingly accepted as one of the most essential elements to manage risks in large and complex engineering systems. Because of relatively high magnitude of consequences in process facilities, they emphasize the importance of fostering an excellent safety culture within the organization. Based on the literature review findings, this study suggests three important rationales for the need of safety culture research effort: safety culture as a root cause, a risk factor and a legal requirement.

In order to take advantage of safety culture as a useful tool to manage risks, the effective assessment of safety culture is imperative. Hence, this study proposes a methodology of measuring safety culture using an approach designed to capture the differences in visible phenomena or activities that are assumed to reveal the level of safety culture. To facilitate this approach, Safety Culture Dimension Matrix based on Mannan *et al.* (2013)'s work [59] and a set of Grading Schemes are developed. As a result, a safety culture assessment questionnaire is also generated as Appendix B.

Moreover, in this study, a Bayesian Belief Network is developed. In the BBN, generic technical failure rate data and mock-up safety culture survey data are combined for a risk analysis. Based on the UFC incident case [86], a risk model is constructed using Hybrid Causal Logic (HCL) [72]. A fault tree and an event tree as parts of the risk model are established based on the case scenario of the incident. For the inclusion of safety culture in the risk model, two levels of Risk Influencing Factors (RIFs) and Safety Culture Influencing Factors (SCIFs) are employed. SCIFs make the transition from qualitative knowledge to quantitative data possible.

The BBN model established in this study illustrates how generic probability of failure of an event is updated with evidences of safety culture assessment results. In overall, the mean values of posterior probability distribution are found to be moderately larger than the generic probability value due to its asymmetrical tails or simply skewness. But it is worth noting that uncertainty associated with organizational factors, *e.g.*, the influence of safety culture, is modeled and represented in this work.

Finally, this socio-technical risk analysis model is assumed to be useful in translating safety culture survey data into a quantitative risk analysis. Several studies have been performed to consider organizational factors into QRA but the use of safety culture assessment results is rarely addressed in such works. In this regard, it is notable that the present work particularly focuses on the measurement of safety culture and its application to a risk analysis. As a result, the model presents the overall risk structure that embraces multiple layers of technical systems and underlying influencing factors that include safety culture. Based on this socio-technical risk structure, the effect of underlying factors on the failure of technical components is investigated. Such analysis is expected to provide useful information for decision making processes to improve safety culture of an organization and thus to manage operational risks in process industries.

5.2 Recommendations for Future Work

First of all, it is recommended to apply the proposed safety culture assessment questionnaire to those working in industries who are familiar with and knowledgeable of process safety culture. Since safety artifacts, *i.e.*, procedures and organizational structure may vary from one organization to another, it is also acceptable to tailor the questionnaire to fit to the particular context of the organization. Once the actual survey data is acquired, more realistic risk representation will become available.

For the BBN modeling in this study, safety culture is considered as a leading indicator that affects the causation of an incident, not affected by such incident. However, those incidents, either being catastrophic or being repeated in a short period of time, are likely to make the existing safety culture unstable. Therefore, it is recommended to model a dynamic BBN model where the occurrence of an incident, *e.g.*, loss of containment, may cause a change in the status of safety culture and, in turn, weakened safety culture influences risks of other incidences.

This study is largely focused on the integration of technical factors and organization factors represented by safety culture. However, real-world cases often entail the consideration of all the risk factors aforementioned: technical, human, organizational and societal factors. Therefore, it is highly recommended to perform further studies to investigate the relationship among these factors and to incorporate all of them in a quantitative risk analysis.

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APPENDIX A

A.1 A List of Artifacts-based Grading Schemes

Artifacts-based Grading Schemes	
1	Management Level-based
2	Top-down-based
3	Bottom-up-based
4	Organization Span-based
5	Budgeting-based
6	Incentive-based
7	Frequency-based
8	Proactive/Reactive-based
9	Timeliness-based
10	Compliance-based
11	Standards-based
12	Information Source-based
13	Expertise-based
14	Safety Status-based
15	Behavior-based
16	Incident type-based
17	Fraction-based

A.2 Details of Artifacts-based Grading Schemes

1. Management Level-basedGrading Scheme

Choices		Point
(a)	CEO, Chief Executive Officer	10/10
(b)	COO, Chief Operating Officer	8/10
(c)	Vice President dedicated to safety	6/10
(d)	Vice President serving multiple duties	4/10
(e)	General manager or equivalent position	2/10

2. Top-down-based Grading Scheme

Choices		Point
(a)	To management to general employees	10/10
(b)	Top management to supervisors	8/10
(c)	Top management to managers	6/10
(d)	Top management to directors	4/10
(e)	Only top management	2/10

3. Bottom-up-based Grading Scheme

Choices		Point
(a)	General employees to top management	10/10
(b)	General employees to directors	8/10
(c)	General employees to managers	6/10
(d)	General employees to supervisors	4/10
(e)	Only for general employees	2/10

4. Organizational Span-based Grading Scheme

Choices		Point
(a)	In all functions including all the corporate staff	10/10
(b)	In engineering (design) and operation (production) functions	8/10
(c)	In operation (production) functions	6/10
(d)	In the division to which the group belongs	4/10
(e)	In the group where the safety information is made	2/10

5. Budgeting-based Grading Scheme

Choices		Point
(a)	Unconditionally provided	10/10
(b)	Evenly provided as other priorities	8/10
(c)	Often influenced by other objectives	6/10
(d)	Only enough to meet legal requirements	4/10
(e)	Less than necessary to comply with regulation	2/10

6. Incentive-based Grading Scheme

Choices		Point
(a)	An appropriate amount of incentive in various forms	10/10
(b)	An appropriate amount of incentive only in cash or similar compensation	6/10
(c)	Limited amount of safety incentive in cash award	2/10

7. Frequency-based Grading Scheme

Choices		Point
(a)	Always (100% of times)	10/10
(b)	Frequently (80% of times)	8/10
(c)	Often (60% of times)	6/10
(d)	Sometimes (40% of times)	4/10
(e)	Rarely (20% or less)	2/10

8. Proactive/reactive-based Grading Scheme

Choices		Point
(a)	Always do proactively (before incidents)	10/10
(b)	Generally do proactively	8/10
(c)	Both proactively and reactively	6/10
(d)	Generally reactively	4/10
(e)	Always reactively (after incidents)	2/10

9. Timeliness-based Grading Scheme

Choices		Point
(a)	Very timely	10/10
(b)	Mostly within a time specified in a procedure	8/10
(c)	Often delayed after the specified time in (b)	6/10
(d)	Seems timely but there is no relevant procedure that requires timeliness	4/10
(e)	Not timely and there is no relevant procedure that requires timeliness	2/10

10. Compliance-based Grading Scheme

Choices		Point
(a)	Procedure is strictly followed and even followed beyond what is required by procedure	10/10
(b)	Procedure is followed most of time	8/10
(c)	Procedure is often ignored	6/10
(d)	Procedure is seldom followed	4/10
(e)	There is no such procedure	2/10

11. Standards-based Grading Scheme

Choices		Point
(a)	Standards are high enough to be said as RAGAGEP*	10/10
(b)	Standards are high enough to meet regulatory requirement	8/10
(c)	Standards barely satisfy regulatory requirement	6/10
(d)	Standards often fail to meet regulatory requirement	4/10
(e)	Standards seldom meet regulatory requirement	2/10

* Recognized and Generally Accepted Good Engineering Practices

12. Information Source-based Grading Scheme

Choices		Point
(a)	Using both internal and external safety information actively	10/10
(b)	Mostly internal information but using major external sources	8/10
(c)	Using various internal safety information	6/10
(d)	Relying on only major internal safety information	4/10
(e)	Rarely using safety information	2/10

13. Expertise-based Grading Scheme

Choices		Point
(a)	In addition to internal personnel, use third part experts based on their performance capabilities	10/10
(b)	In addition to internal personnel, use third party experts based on bidding prices	8/10
(c)	Use internal expert group(s)	6/10
(d)	Use internal expert individual(s)	4/10
(e)	Use internal personnel of limited expertise	2/10

14. Safety Status-based Grading Scheme

Choices		Point
(a)	Safety is always higher than any other disciplines	10/10
(b)	Safety has the equal status as other business objectives	8/10
(c)	Safety often comes after other business objectives (production, profit)	6/10
(d)	Safety gets focused only when incidents happen	4/10
(e)	Safety has never had the equal status as other goals	2/10

15. Behavior-based Grading Scheme

Choices		Point
(a)	Act beyond what is required by safety standards even when nobody is watching	10/10
(b)	Often act above what is required by safety procedures	8/10
(c)	Mostly comply with safety standards	6/10
(d)	Often fail to comply with safety standards	4/10
(e)	Such behaviors are seldom seen	2/10

16. Incident type-based Grading Scheme

Choices		Point
(a)	From catastrophe to near-miss	10/10
(b)	From catastrophe to minor incidents	8/10
(c)	From catastrophe to major incidents	6/10
(d)	Only catastrophe	4/10
(e)	A fraction of catastrophic incidents	2/10

17. Fraction-based Grading Scheme

Choices		Point
(a)	All of them (100%)	10/10
(b)	Much of them (80%)	8/10
(c)	More than a half (60%)	6/10
(d)	Less than a half (40%)	4/10
(e)	Little of them (20%)	2/10

APPENDIX B

B.1 Safety Culture Assessment Questionnaire

Gray empty cells represent the combinations that are already addressed in previous part of the table, *e.g.*, Leadership-Organization & Structure (LS-OS) makes OS-LS pair gray and empty.

Dimension 1	Dimension2	Example(s) of Questions	Grading Scheme
Leadership	Culture & Values	How often does the agenda of high level meetings include no safety issues when it would be necessary?	Frequency-based
		How visibly does management demonstrate the value of safety through his/her action?	Behavior-based
		How proactively (or reactively) does management address process safety concerns?	Proactive/Reactive-based
	Goals, policies & initiatives	How far down does management relay messages of safety goals, policies and objectives to employees?	Top-down-based
		How much support and commitment does management offer to implement safety goals, policies and initiatives?	Budgeting-based
	Organization & structure	What is the position of the Chief Safety Officer?	Management Level-based
		Which management level participates in a joint safety and health committee?	Management Level-based
	Employee engagement & behaviors	How often does management empower expertise (or expert group) when making critical safety decisions versus how often not?	Frequency-based
		How much support does management provide to employees to reinforce an individual's safety authority and responsibility?	Budgeting-based

		How well are responsibilities and accountabilities established and observed for every level of organization?	Compliance-based
	Resource Allocation & performance management	In case it is deemed necessary, how often does management support the health and safety efforts not only in words but also in actions?	Frequency-based
		How much and what kind of incentive does management provide to enhance process safety?	Incentive-based
	Systems, standards & processes	Does your company have a written procedure that requires managers to serve in safety roles and receive intensive process safety training?	Compliance-based
		Is compliance with safety standards an unnegotiable condition of employment?	Compliance-based
	Metrics & reporting	How far up in the management structure are safety performances or statistics reported?	Management Level-based
		How often does management respond to employee concerns or reporting versus how often they neglect to respond?	Frequency-based
	A continually learning organization	Does your manager attend and actively participate in safety training sessions and safety drills?	Behavior-based
		Does your manager participate directly in the investigation when an incident occurs?	Behavior-based
		In what timely manner do managers and supervisors communicate safety information with members in the group that he/she leads?	Timeliness-based
	Verification & audit	How do managers monitor junior members' commitment to safety?	Compliance-based
		How frequently does management reinforce the fundamental importance of safety to the organization?	Frequency-based
		How wide sources of safety information does management utilize to ensure that safety messages are communicated?	Information Source-based
		Is there a formal and effective management review system for safety performance and safety culture development?	Compliance-based

Culture & Values	Leadership		
	Goals, policies & initiatives	How much attention do safety accomplishments have when compared with other business successes?	Safety Status-based
	Organization & structure	What status and compensation do safety professionals in your organization have when compared with other key members?	Safety Status-based
	Employee engagement & behaviors	How often do you see that standing up for safety is perceived as a positive and strong action when there is good reason for it?	Frequency-based
		How often are employees treated with respect following an incident versus how often not?	Frequency-based
	Resource Allocation & performance management	How does your company make decisions to allocate budget on safety when compared with other business objectives?	Safety Status-based
		How often does your organization compromise safety to meet short-term cost or production targets?	Frequency-based
		How much of resources does your company allocate on preventing incidents and eliminating hazards rather than responding to incidents?	Proactive/Reactive-based
	Systems, standards & processes	How do people in your organization behave in compliance with safety standards?	Compliance-based
		Are your company's safety standards high enough to ensure the safety of tasks to be performed?	Standards-based
		Is there a written program that lists the individual's responsibility about process safety goals and policies?	Compliance-based
		Does your company have a zero tolerance policy about deviation from safety standards?	Compliance-based
	Metrics & reporting	What is the primary motivation of reporting incidents: compliance, reward/punishment or voluntary concerns for other's safety?	Proactive/Reactive-based
		How does your organization monitor and respond to leading and lagging indicators?	Incident type-based

	A continually learning organization	How are safety culture, vision, expectations, roles, responsibilities and standards discussed and trained?	Bottom-up-based
		Does your company have formal plans that require employees to enhance their safety-related knowledge and expertise?	Compliance-based
	Verification & audit	Does your company maintain its vigilance through real-time drills, rigorous safety audits and inspections?	Standards-based
		How does your company perform periodic and special safety studies?	Expertise-based
		Do investigations of process safety failures identify root causes or underlying causes?	Frequency-based
Goals, policies & initiatives	Leadership		
	Culture & Values		
	Organization & structure	How frequently do you receive safety information from the company?	Frequency-based
	Employee engagement & behaviors	How often are employees involved in setting goals, policies and initiatives regarding process safety?	Frequency-based
		Does your company have a written procedure that allows employees to participate in a planning or design process of safety initiatives?	Compliance-based
	Resource Allocation & performance management	How does your organization support new safety programs and initiatives for their implementation by making capital investment?	Budgeting-based
		Are the consequences of willful violations of safety policies, procedures, and rules established and actively enforced?	Compliance-based
	Systems, standards & processes	Does your company have a formal system in which employees establish and review process safety goals?	Compliance-based
	Metrics & reporting	Does your company have a policy that imposes discipline for those who fail or intentionally omit to report?	Compliance-based

	A continually learning organization	How much are lessons learned from incidents considered in reviewing and resetting safety goals, policies and safety initiatives?	Fraction-based
	Verification & audit	Does your company monitor the effectiveness of new policies and initiatives until they have full taken root and become self-sustaining?	Compliance-based
		How frequently are safety policies and initiatives replaced or re-engineered before they are deeply embedded in the organization?	Frequency-based
Organization & structure	Leadership		
	Culture & Values		
	Goals, policies & initiatives		
	Employee engagement & behaviors	Does your company have a joint safety committee comprised of management and worker representatives?	Compliance-based
	Resource Allocation & performance management	How widely do safety departments provide safety expertise, develop safety goals and policies and manage safety communications throughout the company?	Organization Span-based
	Systems, standards & processes	Does your company provide opportunities for job rotation to decrease errors due to monotony?	Compliance-based
	Metrics & reporting	Do you have dual lines of reporting, one up through the operating site leader and the other through the dedicated safety personnel?	Compliance-based
	A continually learning organization	How broadly are lessons learned from investigations of incidents and near misses, audits, and hazard assessments?	Organization Span-based
	Verification & audit	Are safety audit protocols consistently applied at different parts in the organization?	Compliance-based
Employee engagement &	Leadership		
	Culture & Values		

behaviors	Goals, policies & initiatives		
	Organization & structure		
	Resource Allocation & performance management	Do managers and safety professionals have opportunities to speak up for safety when a proposed budget seems to threaten safety? How often versus how often not?	Frequency-based
		Does your company have a formal budgeting process to give enough resources to support process safety initiatives?	Compliance-based
		Does your company manage workforce issues so that staffing levels and fatigue are appropriately controlled?	Compliance-based
	Systems, standards & processes	Does your company have a peer review program that helps employees take some responsibility for safety performance of their co-workers?	Compliance-based
		Does your company reinforce that all employees have responsibilities to themselves, their co-workers, the company, and the community?	Organization Span-based
	Metrics & reporting	How open and responsive are lines of communication between peer workers, and up and down the organizational hierarchy?	Timeliness-based
	A continually learning organization	How often are workers asked to participate in incident investigations versus how often not?	Frequency-based
		Do you learn from peers at internal sources as well as external training opportunities?	Information Source-based
	Verification & audit	How are employees' safe/unsafe behaviors reviewed by managers?	Compliance-based
		How well and fairly is your safety performance recognized and evaluated by peers and managers?	Safety Status-based
Resource Allocation & performance management	Leadership		
	Culture & Values		
	Goals, policies & initiatives		

	Organization & structure		
	Employee engagement & behaviors		
	Systems, standards & processes	Are safety expenditures made systematically and based on effective risk assessment and cost-benefit analysis?	Compliance-based
		How timely is management response to unacceptable performance of process safety requirements?	Timeliness-based
		How many of Job Safety Analyses (JSA) are completed, of what quality?	Fraction-based
		Do managers and employees of your company follow operational procedures without shortcuts or unapproved deviations?	Compliance-based
	Metrics & reporting	Does your company recommend to report incidents by giving proper incentives?	Incentive-based
		Does your organization maintain standards of performance through timely reporting of performance statistics?	Timeliness-based
	A continually learning organization	How well do your company utilize learnings from previous accidents, near misses and non-compliant behaviors?	Frequency-based
	Verification & audit	Does your company tolerate an employee's repeated unsafe acts and failure to comply with safety procedures and requirements?	Compliance-based
		Does your company perform formal root cause analysis to identify root causes and thus prevent recurrence of incidents in the future?	Compliance-based
Systems, standards & processes	Leadership		
	Culture & Values		
	Goals, policies & initiatives		
	Organization & structure		

	Employee engagement & behaviors		
	Resource Allocation & performance management		
	Metrics & reporting	Is a formal system established to ensure employees to report potential hazards?	Compliance-based
	A continually learning organization	How much are learnings from incidents and hazard assessment used for design of the facility and procedures?	Fraction-based
	Verification & audit	Does a formal communication system exist for sharing information on process safety standards?	Compliance-based
		Is this communication system monitored to ensure that the information is reaching all facility personnel?	Top-down-based
		Are there formal tracking systems that ensure process safety recommendations and suggestions are imposed for their timely resolution?	Compliance-based
		Does your company have a tiered audit process that utilizes both internal personnel and third parties?	Expertise-based
		When there is a change to a process, facility or organization, how timely are operating procedures updated accordingly?	Timeliness-based
Metrics & reporting	Leadership		
	Culture & Values		
	Goals, policies & initiatives		
	Organization & structure		
	Employee engagement &		

	behaviors		
	Resource Allocation & performance management		
	Systems, standards & processes		
	A continually learning organization	How much of the lessons are captured into design, procedures, training, maintenance and other safety programs?	Fraction-based
		How does your company define incidents that need further investigation? Catastrophic consequence and/or near misses?	Incident type-based
		How widely are investigation results and lessons shared across the organization?	Organization Span-based
	Verification & audit	Does your company verify the adequacy and effectiveness of safety audits by using metrics such as the number of audits schedules vs. conducted?	Compliance-based
A continually learning organization	Leadership		
	Culture & Values		
	Goals, policies & initiatives		
	Organization & structure		
	Employee engagement & behaviors		
	Resource Allocation &performance management		
	Systems,		

	standards & processes		
	Metrics & reporting		
	Verification & audit	How does your organization use audit results as an important process safety information?	Information Source-based
		Does your company have a written procedure to ensure process hazard analysis and incident investigation are appropriately performed?	Compliance-based
Verification & audit	Leadership		
	Culture & Values		
	Goals, policies & initiatives		
	Organization & structure		
	Employee engagement & behaviors		
	Resource Allocation & performance management		
	Systems, standards & processes		
	Metrics & reporting		
	A continually learning organization		