ADVANCED QUANTITATIVE RISK ASSESSMENT OF OFFSHORE GAS PIPELINE SYSTEMS

A Thesis Submitted to Liverpool John Moores University
for the Degree of Doctor of Philosophy

MSc, BEng

SEYED MOHAMMADREZA MIRI LAVASANI

Liverpool Logistics, Offshore and Marine (LOOM) Centre
School of Engineering, Technology and Maritime Operations

March 2010

Abstract

This research has reviewed the current status of offshore and marine safety. The major problems identified in the research are associated with risk modelling under circumstances where the lack of data or high level of uncertainty exists. This PhD research adopts an object-oriented approach, a natural and straightforward mechanism of organising information of the real world systems, to represent the Offshore Gas Supply Systems (OGSSs) at both the component and system levels. Then based on the object-oriented approach, frameworks of aggregative risk assessment and fault tree analysis are developed. Aggregative risk assessment is to evaluate the risk levels of components, subsystems, and the overall OGSS. Fault trees are then used to represent the cause-effect relationships for a specific risk in the system. Use of these two assessment frameworks can help decision makers to obtain comprehensive view of risks in the OGSS.

In order to quantitatively evaluate the framework of aggregative risk, this thesis uses a fuzzy aggregative risk assessment method to determine the risk levels associated with components, subsystems, and the overall OGSS. The fuzzy aggregative risk assessment method is tailored to quantify the risk levels of components, subsystems, and the OGSS. The proposed method is able to identify the most critical subsystem in the OGSS. As soon as, the most critical subsystem is identified, Fuzzy Fault Tree Analysis (FFTA) is employed to quantitatively evaluate the cause-effect relationships for specific undesired event. These results can help risk analysts to select Risk Control Options (RCOs) for mitigating risks in an OGSS. It is not financially possible to employ all the selected RCOs. Therefore, it is necessary to rank and select the best RCO. A decision making method using the Fuzzy TOPSIS (FTOPSIS) is proposed to demonstrate the selection of the best RCOs to control the existing risks in the system.

The developed models and frameworks can be integrated to formulate a platform which enables to facilitate risk assessment and safety management of OGSSs without jeopardising the efficiency of OGSSs operations in various situations where traditional risk assessment and safety management techniques cannot be effectively applied.

Acknowledgments

I firstly would like to give very special thanks to my three supervisors, Prof. J. Wang, Dr. Z. Yang and Dr J. Finlay in the School of Engineering, Technology and Maritime Operations at Liverpool John Moores University (LJMU) for their stimulating suggestions, constructive comments and constant encouragement. These special thanks are conveyed not only for their continuous support, encouragement and guidance through this research, but also for their optimism and kindness. I learnt many research skills from Prof. J. Wang with his sparkling ideas and innovative thinking in doing research, which are instrumental in the development of the methodological framework and structure of this study. Meanwhile, his continuous encouragement and optimistic attitude have been influencing me and cultivating my enthusiasm in this research. Also, I have derived a great deal of pleasure of working with my colleagues at the Liverpool Offshore, Logistics and Marine (LOOM) Centre and am ever so grateful for their wit of providing the critical forum for the research.

My heartfelt thanks are also given to my parents for giving me life, educating me, and encouraging me to pursue my interests. They may never read this thesis, but they do present the most valuable part of my life. In addition, I would like to give special thanks to my brother (Milad) and uncle (Vahid) for all their constant and loving encouragement, especially in times of hardship. Last but not least, I would like to give my wholehearted thanks to my wife (Elmira) for her patience and continuous support during the research.

Seyed Mohammadreza Miri Lavasani

Table of contents

List of tables

List of figures

Abbreviations

Abbreviations	Descriptions
AA	Average Agreement
AHP	Analytical Hierarchy Process
ALARP	As Low As Reasonably Practicable
AMV	Annulus Master Valve
API	American Petroleum Institute
AVV	Annulus Vent Valve
AWV	Annulus Wing Valve
BEs	Basic Events
CC	Capital Cost
CCO	Consensus COefficient
CCPS	Centre Chemical Process Safety
CON	CONsequence
CSE	Concept Safety Evaluations
CT	Christmas Tree
DCR	Design and Construction Regulations
DETR	Department of the Environment, Transport and the Regions
DSS	Decision Support System
EA	Environmental Agency
ER	Evidential Reasoning
ETA	Event Tree Analysis
FAHP	Fuzzy AHP
FAR	Final Aggregative Risk

FFTA	Fuzzy FTA
FMADM	Fuzzy MADM
FMECA	Failure Mode, Effects and Criticality Analysis
FRA	Fuzzy Risk Assessment
FSA	Formal Safety Assessment
FTA	Fault Tree Analysis
FTOPSIS	Fuzzy TOPSIS
F-VI	Fussell-Vesely Importance
HAZOP	HAZard Operability
HES	Health, Environment and Safety
HSE	Health & Safety Executive
IC	Insurance Cost
IDS	Intelligent Decision System
MADM	Multiple Attribute Decision Making
MCDM	Multiple Criteria Decision Making
MCs	Markov Chains
MCSs	Minimal Cut Sets
MMS	Mineral Management Services
NCS	Norwegian Continental Shelf
NIS	Negative Ideal Solutions
NOPSA	National Offshore Petroleum Safety Authority
NPD	Norwegian Petroleum Directorate
NRC	National Research Council
NTSB	National Transportation Safety Board
OEA	Office of Energy Assurance
OGSS	Offshore Gas Supply System

OOA	Object-Oriented Approach
OREDA	Offshore RElaibility DAta
PHA	Preliminary Hazard Analysis
PIA	Pressure Indicator Alarm
PIS	Positive Ideal Solutions
PMV	Production Master Valve
PRA	Probabilistic risk assessment
PRR	Pressure Reducing Regulator
PSA	Petroleum Safety Authority
PS	Pressure Switch
PSR	Pipeline Safety Regulations
PTT	Pressure Transient Test
PV	Pneumatic Valve
PWV	Production Wing Valve
QRA	Quantitative Risk Assessment
RA	Relative Agreement
RC	Relative Closeness
RCOs	Risk Control Options
RD	Rupture Disk
REL	RELiability
RMM	Risk Matrix Method
RRW	Risk Reduction Worth
SCR	Safety Case Regulations
SCSSV	Surface Controlled Subsurface Safety Valve
SIS	Safety Instrumented System
SMS	Safety Management System

SRVs	Safety Relief Valves
SSIVs	Sub Sea Isolation Valves
SSSV	Sub Surface Safety Valve
SSV	Surface Safety Valve
TC	Tree Cap
TDS	Top Decrease Sensitivity
TE	Top Event
TPV	Three Port Valve
UKCS	United Kingdom Continental Shelf
UKOOA	U.K. Offshore Operator Association
US GoM	United States Gulf of Mexico
USOCS	U.S. Outer Continental Shelf
WBE	Well Barrier Element

Chapter 1

Introduction

Summary

This chapter first discusses the background of the research and in doing so highlights the inherent problems which exist in offshore pipeline systems today when applying risk assessment analysis. The objectives and hypotheses of the research serve to set out a logical structure of the research which is aimed at addressing the inherent problems outlined. This is followed by a brief description of the research methodology and the scope of the study. Finally, the structure of this thesis is given.

1.1 Background

The essential function of an Offshore Gas Supply System (OGSS) is to transport hydrocarbons from the reservoir to the processing equipment in a cost-effective and safe manner. The importance of offshore system safety has been recognized and accepted for a long time, and significant improvements concerning both design and operating procedures have been made. In spite of these improvements, failures still occur and will most likely continue to occur in the future. The need for continued focus on offshore system safety is exemplified by the gas blow-out in 2005 on the Snorre tension leg platform operating on the Norwegian Continental Shelf (NCS) (Aven & Vinnem, 2007). According to the Petroleum Safety Authority (PSA) in Norway the accident could have resulted in a major accident with the loss of many lives.

The offshore industry continues to develop new well and pipeline designs for challenging reservoir conditions. For example, the industry now focuses on finding and developing the smaller/marginal fields in the southern part of the NCS. In search for new large and profitable fields, the industry moves north and into deeper water. This development results in production in more environmentally sensitive areas and in operations under more hostile weather conditions. A similar development is seen in Russia where offshore fields in the Barents region are being planned.

To develop marginal fields it is expected that the operators of offshore fields will be more directed towards subsea systems and investments in new development concepts and technologies. An example is Subsea high integrity pressure protection systems , where pipelines are not rated for the full pressure and a Safety Instrumented System (SIS) is installed on the seafloor to close the flow if high pressure above an acceptable level occurs. The application of first subsea high integrity pressure protection systems on the NCS is the Kristin field (Aven & Vinnem, 2007). The field started production in October 2005. The trends mentioned above indicate that new technology applied in more challenging fields will require continued focus on risk assessment and management in the future.

According to Hirsch et al. (2005) the oil and gas production will soon peak and there may be a mismatch between the demand for and the supply of petroleum and this situation will not be temporary. Peaking will create a severe liquid fuel problem for the transportation sector. Peaking will result in dramatically higher oil prices, which will cause economic hardship in the industrial countries, and even worse problems in the developing countries. With the expected mismatch between demand and supply, it is likely that there will be an increased pressure on safety of OGSSs.

In Norway, the NORSOK D-010 standard (NORSOK, 2004) describes offshore well integrity requirements, where *well integrity* is "the application of technical, operational, and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the life cycle of the well". Well integrity has always been focused on the design of new wells, but well integrity in the operational phase is now of increasing concern. Because of high oil and gas prices, new technology for increased recovery, and government incentives, it is now possible and profitable to extend production beyond the initially assumed design life. However, life extension may result in more frequent critical failures involving leakages to the environment. The outcome of such leaks can be catastrophic. According to Corneliussen et al. (2007) 10% of the offshore wells in the United Kingdom Continental Shelf (UKCS) were shut-in due to well integrity problems during the last five years. The article refers to a study based on interviews with 17 UKCS operators. Approximately 83% of these operators experienced well integrity problems. Other topics highlighted in Corneliussen et al. (2007) are:

- Little is known about the implications of operating wells beyond their design lives, and UK operators found growing concerns about the safety, environmental, and economic standards associated with well structural integrity.

- Some operators believe that well functionality can be maintained, regardless of age, through inspection, monitoring and maintenance. Nevertheless, 87% of the operators questioned believe that the incidence of structural integrity problems is increasing and will continue to do so.

It is likely that the NCS situation is comparable to the UKCS situation because there are many similarities in field age, type of installations, operating practice, etc. Well integrity is also a major concern in the United States Gulf of Mexico (US GoM). A study carried out on behalf of the Mineral Management Services (MMS) concludes that more than 8000 wells in the US GoM Outer Continental Shelf experienced well completion leaks (Bourgoyne et al., 2003).

The increased emphasis on well integrity in the operational phase is reflected in recent regulations and standards. In Norway, for example, NORSOK D-010 describes the requirements for "*Well Integrity in drilling and well operations*", while the American Petroleum Institute (API) currently develops a recommended practice for handling of annular casing pressure in the US GoM. The working title is API RP904 – Annular Casing Pressure Management for Offshore Wells. Independent of the industry sector, there is a global trend towards functional requirements (what is to be achieved) rather than deterministic/rule based requirements (what to do) in high-risk industries. A main reason for this change is to enable the industry to cope with new technology rather than restricting the development. As a consequence of more functional requirements there is an increased focus on risk assessment methods to demonstrate acceptable risk.

Historically, offshore safety regulations were introduced following an accident or a series of major accidents, intending to address the most obvious causes. Over years, after a number of defining accidents including the capsize of the semi-submersible rig "Alexander Keilland" in 1980 and the explosion aboard " Piper Alpha" platform in 1988, the way in which safety is reviewed has been alerted. The characteristic of offshore safety has evolved from a reactive manner toward a proactive attitude where a goal-setting and risk-based regime is required since the introduction of the safety regulations including Safety Case Regulations (SCR) and Formal Safety Assessment (FSA) in the 1990s. The main objective of these safety regulations is to ensure that risk has been reduced to the level of As Low As Reasonably Practicable (ALARP) and Risk Control Options (RCOs) proposed are cost-effective.

In general, the tendency of maritime risk assessment is that it is not only used for verification purposes in design and operational process of marine and offshore systems, but also for making decisions from the early stages (Wang, 2002). Accordingly, interest in the improvement of the safety of large engineering systems based on the safety management from the initial stages has been growing considerably within both the regulatory bodies and industry. However, since such a safety analysis is conducted at initial stages, circumstances of the lack or incompleteness of data, or the low or none relevance of generic data of specific areas in question are inevitably encountered. This would cause a high level of uncertainty that may significantly undermine the conclusion acquired based on the traditional quantitative risk assessment and safety management techniques. Consideration of these uncertainties may drive estimated risk level appreciably upward or downwards from the initial calculated results. Regardless of whether these estimated results are initially assessed as optimistic or pessimistic estimates, for instance, an upward revision could result from the consideration of the effect of a limited incident reporting in relation to its failure mode definition. Thus, the risk results evaluated under such circumstances may not be acquired with confidence.

Due to the fact that detailed and historical safety related data within offshore pipeline system is scarce, the issue as to the lack or incompleteness of data is also imposed on offshore pipeline system safety studies. This inevitably increases the difficulty of risk assessment and safety management in offshore pipeline systems.

1.2 Research objectives and hypothesis

The primary aim of this study is to develop a novel Quantitative Risk Assessment (QRA) methodology for an effective risk assessment and management of OGSSs. QRA is a new approach in offshore well and pipeline operations, which has evolved after the occurrence of some serious accidents, emphasising the need of using a risk-based management system in order to proactively ensure a strategic and scientific oversight of offshore well and pipeline safety and pollution prevention. The development of an advanced QRA is a vital part of this thesis as it sets the foundation of the whole project. In order to achieve such an aim, this thesis has the following four main objectives.

A clear understanding of the system and the system boundaries is a key factor in any analysis, including risk analysis. By understanding of the system, suitable risk analysis methods and input data can be identified. Therefore, the first objective of this research work is to develop qualitative frameworks for representing the hierarchical relationships of components, subsystems and overall OGSSs. Frameworks of risk assessment are developed based on the concept of an Object-Oriented Approach (OOA) (Elshorbagy & Ormsbee, 2006) and characteristics of OGSSs.

The second objective is to develop a method to evaluate risks of components, subsystems and overall OGSSs. The modelling techniques used to achieve the second objective are a combination of Fuzzy Risk Assessment (FRA) method and Analytical Hierarchy Process (AHP). The integration of FRA and AHP addresses the problems associated with a large amount of subjective expert judgments required.

The third objective is to provide a method for assessing fault trees of OGSSs. Results of this assessment are likelihood of the occurrence for a specific event and importance measures of possible contributing causes. Based on the above risk analysis results, a MADM technique (Fuzzy Techniques for Order Preference by Similarity to an Ideal Solution (FTOPSIS)) is used to rank the alternatives of RCOs.

The objectives are also carried out to test the hypothesis of the research. This thesis is designed to test a hypothesis that it is possible to develop a new QRA capable of tackling a variety of systems in industry, with special consideration placed on OGSSs. This hypothesis requires historical data, available data and expert judgment to be presented in risk-based tools and techniques.

1.3 Statement of problem

As aforementioned due to lack of data or incompleteness of data, uncertainties may significantly undermine the conclusion acquired based on the traditional quantitative risk assessment and safety management techniques. Accordingly, the research problem for this PhD study is shown as follows:

How are risk assessment and safety management conducted with confidence under circumstances where the unavailability or incompleteness of data or a high level of uncertainty exists?

The challenge of this thesis is to extract the required information, from objective and subjective sources, in order to produce a new QRA methodology. The process of gathering data, the use of existing data or reliance on expert judgements has shown to be a troublesome process in terms of accuracy (Pillay & Wang, 2003). The gathering of objective data in order to apply a modelling technique can be difficult as it generally requires many months or even years to attain sufficient data. The use of subjective data gathered from expert judgments can often come in a form which requires standardisation with existing data in order to establish a consistency of data ensuring confidence in the modelling results. The combining of both objective and subjective data requires elicitation in order to establish the data which is required to apply advanced modelling techniques to OGSSs.

1.4 Delimitations of the scope

Since the objective of this PhD research is to provide a platform for risk assessment and safety management addressing OGSSs safety with confidence in circumstances of the lack or incompleteness of data, the subjective data for the test cases demonstrated in this study are hypothetically prepared by the author together with his supervisors and experts specialising in the offshore industry. This is because of the difficulty of acquiring real industrial data due to the many reasons including the confidentiality of data of this kind.

1.5 Justification of research

In the risk assessment and safety management research, management of the effects caused by uncertainty and complexity of systems is an important issue. A hierarchical framework is an effective way to deal with complexity. It decomposes the complex problem into more manageable subsystems or components, and represents the contributions to overall system by its components and subsystems. Thus it has the ability to perform risk evaluations at both the component and system levels. As aforementioned, causes of uncertainty are diverse. Thus, regardless of what approaches are to be applied, it always depends upon human judgements to manage such negative effects. In other words, the deficiencies of risk modelling resulting from lack of data or high level of uncertainty must be made up by means of the general evaluation capacity of humans capable of grasping the essence of an object, even if it is vague and unclear. One feasible way to model such a situation under a high level of uncertainty is to use fuzzy set theory. Fuzzy set theory, formalised in 1965, has been applied in different fields. Its application in system safety and reliability analysis could prove to be useful since such analysis often requires the use of subjective judgment and uncertain data. When dealing with the safety of a system using fuzzy set theory, the parameters including occurrence likelihood and severity of possible consequences can be judged and described using linguistic terms and their associated memberships. These fuzzy variables can then be synthesised with confidence using an AHP (Lee, 1996; Chen, 2001; Sadiq & Husain, 2005; Zeng et al., 2006; Wang & Elhag, 2007) or some other techniques such as FTA (Andrews & Moss, 2002; Henley & Kumamoto, 1981) or TOPSIS (Hwang & Yoon, 1981; Chen, 2000; Li & Yang, 2004; Herrera et al., 2005)

With the awareness of the effectiveness of hierarchies in dealing with complexity, this study adopts hierarchies, but based on an OOA to represent the relationships in offshore pipeline systems, and to develop frameworks for risk assessment. Meanwhile, fuzzy set theory, AHP, Evidential Reasoning (ER) (Yang & Xu, 2002) and FTA are integrated with these hierarchies to generate quantitative results. This research is composed of four integrated technical parts as follows (Figure 1.1).

1.5.1 Object Oriented Approach (OOA) of OGSSs

Firstly, an OOA is proposed in this research to deal with the complexity (Simons, 1982; Courtois, 1985) of OGSSs and to generate a hierarchical structure for risk assessment. OOA is a method that represents engineering systems in terms of objects (Booch, 1994; Solomatine, 1996; Ross et al, 1992; Black & Megabit, 1995; Liu & Stewart, 2003; Crossland, et al., 2003; Elshorbagy & Ormsbee, 2006). Every component in an OGSS is viewed as an object, and the overall system is viewed as a set of objects that are interconnected with each other. All risk factors about the components are considered as attributes or behaviours of objects. Furthermore, with the generalization and aggregation relationships, object-oriented hierarchical structures can be easily formed to represent the whole/part relationships and interconnections between objects in an OGSS.

1.5.2 Fuzzy Risk Assessment (FRA) of OGSSs

Aggregative risk assessment is composed of two stages, the component level and the system level. Firstly, state transition diagrams of objects describe the relationships between hazards, object failure states, and object risks, which thus provide a hierarchical framework for risk assessment at the component level. In this hierarchical framework, risk of an object is at top level followed by its relative failure states that are at its immediate lower level. Hazards or threats are at the bottom level in this framework. This indicates that risks of an object are determined by its failure states, which are in turn determined by the threats or hazards directly related to them. This research represents each hazard or threat in terms of its likelihood of occurrence and severity of possible consequences that are represented by fuzzy numbers. The risk of a component is thus an aggregative measure that is determined by aggregating the risks of threats or hazards along the hierarchical structure.

Secondly, for the risk assessment at the system level, an object-oriented whole/part relationship structure is used to determine aggregative risks of OGSSs. In this hierarchical framework, The OGSS is at the top level, its subsystems and components are at relatively lower levels. Therefore, the risk of the overall system is an aggregative measure which is contributed by the risks of its subsystems and components along the hierarchical structure. With the development of the conceptual framework for aggregative risk assessment, fuzzy set theory and an aggregation method (i.e. AHP) (Leung & Cao, 2000; Bozdağ et al., 2003; Kwong & Bai, 2003; Kahraman et al., 2003; Büyüközkan, 2004; Büyüközkan et al., 2004; Erensal et al., Huang et al., 2005; 2006; Tüysüz & Kahraman, 2006; Chan & Kumar, 2007) are used to produce quantitative evaluations.

1.5.3 Fuzzy Fault Tree Analysis (FFTA) of OGSSs

FTA is considered in this study to represent the cause-effect relationships in OGSSs. Fault tree analysis, a deductive reliability and risk analysis technique, can answer the question of how the system could produce a failure. With the help of FTA, risk analysts will know which component in the system is more critical and which risk scenario is more significant (Pillay & Wang, 2003). Meanwhile risk contributions and uncertainty contributions can also be obtained to support selection of mitigation measures (Furuta & Shiraishi, 1984; Shu et al., 2006) and asset management. However the development of fault trees is still as much an art as a science. This research uses an object-oriented approach to generate fault tree structures via two steps. Firstly, object states transition diagram is used to generate the fault trees at the component level. Then, interconnections between components in an OGSS are used to develop fault trees at system level. After fault trees have been constructed, FFTA (Misra & Weber, 1990; Liang & Wang, 1993; Cheng & Mon, 1993; Lin & Wang, 1997; Dong & Yu, 2005; Ping et al., 2007; Pan & Wang, 2007) is adopted to obtain quantitative results.

1.5.4 Application of Multiple Attribute Decision Making (MADM) in a fuzzy environment for selection of the best RCO in OGSSs

Due to the complexity of OGSSs, conventional quantitative risk assessment may not be capable of providing sufficient risk management information. The selection of different mitigating and preventive alternatives (i.e. RCOs) often involves competing and conflicting criteria (cost and benefit), which requires sophisticated decision making methods. The decision making in this study is the analysis with multiple objectives that have both a quantitative and a qualitative nature. It is obvious that much knowledge in the real world is fuzzy rather than precise. In an OGSS ranking/selecting problem, decision data of MADM problems is usually fuzzy, crisp, or a combination of the two. Hence, a useful model should be able to handle both fuzzy and crisp data. Since imprecision and ambiguity in the calculation of a performance rating are incorporated into MADM, fuzzy set theory provides a mathematical framework for modelling them. The research method employed is a Fuzzy TOPSIS (FTOPSIS) (Zimmermann & Zysno, 1985; Teodorovic, 1985; Zanakis et al., 1998; Jee & Kang, 2000; Chen, 2001; Yong, 2006; Li, 2007) approach. It is one of the techniques that are developed to solve

MADM problems. By using this technique, subjective judgement with uncertainty and precise data can be consistently modelled under a unified framework. Figure 1.1 demonstrates the logic relationship among the proposed methods in this PhD research.

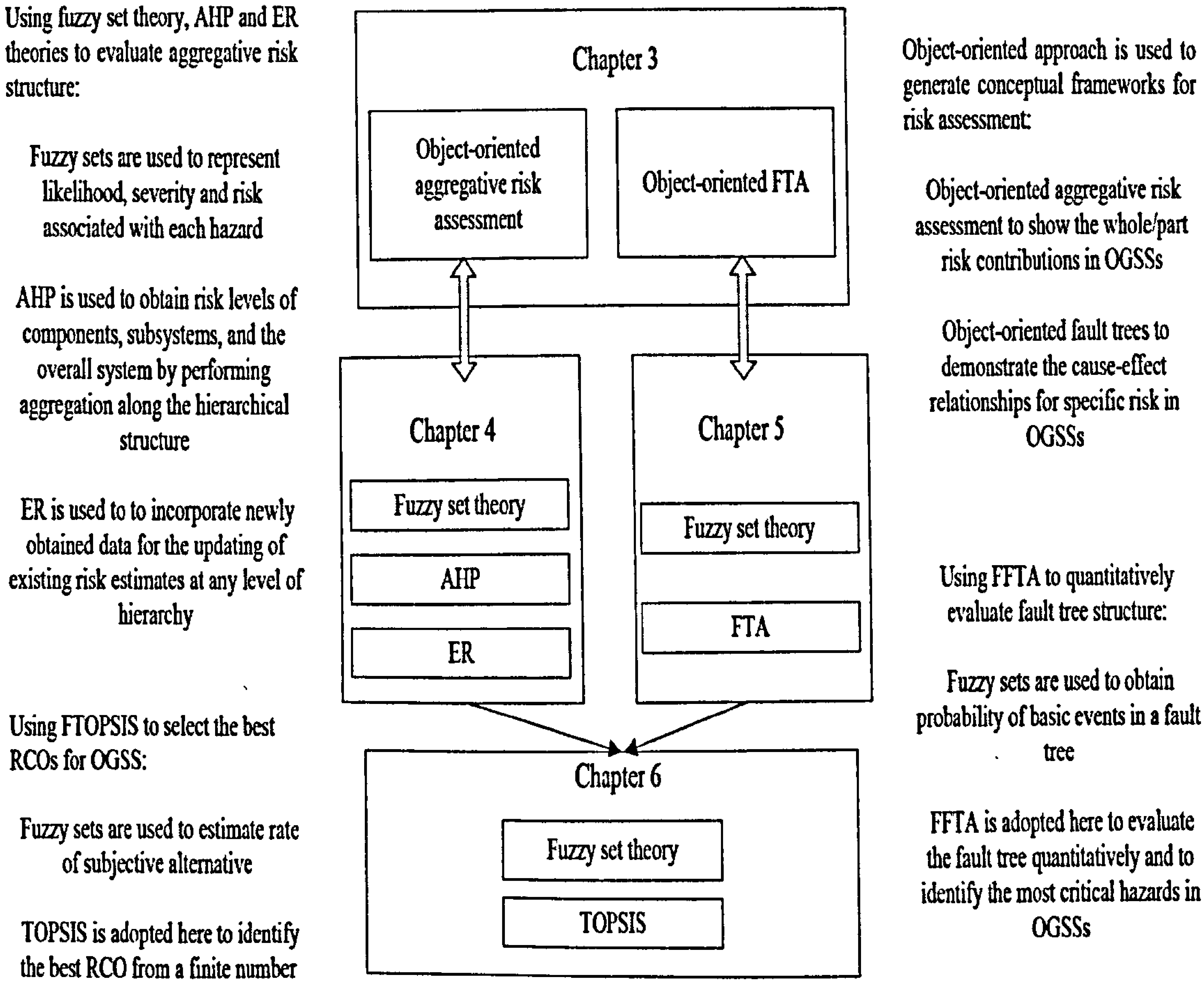


Figure 1.1 Logic relationships among the methods used in this research

1.6 Structure of thesis

The scope of this research is to develop an advanced QRA methodology, utilising varying information from both objective and subjective sources. The purpose of the advanced QRA is to a) present the relation among components, subsystem and the overall OGSS, b) estimate risk of components, subsystem and the overall OGSS, c) identify an event or a group of events that has the highest contribution to an incident and d) provide the best RCOs for mitigating risk of the system.

This thesis is compiled of seven chapters. Chapter 1 has outlined a brief introduction relating to the background of the research, an introduction of the research hypothesis, a statement highlighting the problems currently encountered, methodology and the scope of this thesis.

Chapter 2 reviews the current status of offshore and marine safety. The frameworks of the safety regulations including SCR and FSA are also discussed. The strengths and shortcomings of maritime risk assessment techniques commonly applied are examined, providing a critical review for their current practices. According to the reviews, comments are obtained to express the limitations associated with the conventional methods and to propose possible resolutions overcoming these limitations. Then the methodology background of the current study is justified and briefly discussed at the end of the chapter.

Chapter 3 aims to develop conceptual frameworks for aggregative risk assessment and FTA of OGSSs. Firstly, it introduces the OOA and its potential application in organising complex information in OGSSs. Then a hierarchical structure of OGSSs is developed based on the concepts of OOA. State transition diagrams are used to represent the cause-effect relationships of risks at the component level. Frameworks of aggregative risk assessment are formed based on the hierarchical whole/part relationships of OGSSs and components state transition diagrams. Frameworks of fault trees are established according to the interconnections among components state transition diagrams. These frameworks can give useful information for decision makers in OGSSs.

Chapter 4 introduces the method to quantitatively evaluate the hierarchical frameworks of aggregative risk assessment developed in Chapter 3. Fuzzy set theory is adopted here to determine the risk levels of hazards/threats which are at the bottom level of the hierarchical structure. Fuzzy AHP (FAHP) is adopted as an aggregative method to evaluate risk levels of components, subsystems, and the overall OGSS along the hierarchy. The proposed method is able to identify the most critical subsystem in OGSS.

As soon as, the most critical subsystem is identified (Chapter 4). Chapter 5 applies FFTA to quantitatively evaluate the fault tree of the most critical subsystem. In the FFTA method, the likelihood of Top Event (TE) and importance measures of contributing factors are investigated. The results of this analysis are used to prioritise the components and hazards for specific risks and assist risk analysts in making rational decisions.

Result of Chapter 4 and Chapter 5 help the analyst to select RCOs for mitigating the risk of subsystem and OGSS. Chapter 6 proposes a Fuzzy MADM (FMADM) method which is suitable for treating group decision making problems under a fuzzy environment for selecting and ranking of the best RCOs from a cost-benefit viewpoint for mitigating risk of systems. A decision maker often encounters the problem of selecting a solution from a given set of alternatives. The chosen alternative is the one that most likely meets certain predefined objectives/goals. A MADM method provides engineering and management decision aids in evaluating and/or selecting the best RCO from a finite number of alternatives which are characterised by multiple attributes.

Chapter 7 concludes the overall study. The chapter begins with discussing the main conclusions. The limitations of this research are also given together with possible future research which can expand and explore this body of research. A diagrammatic guide to this thesis is shown in Figure 1.2.

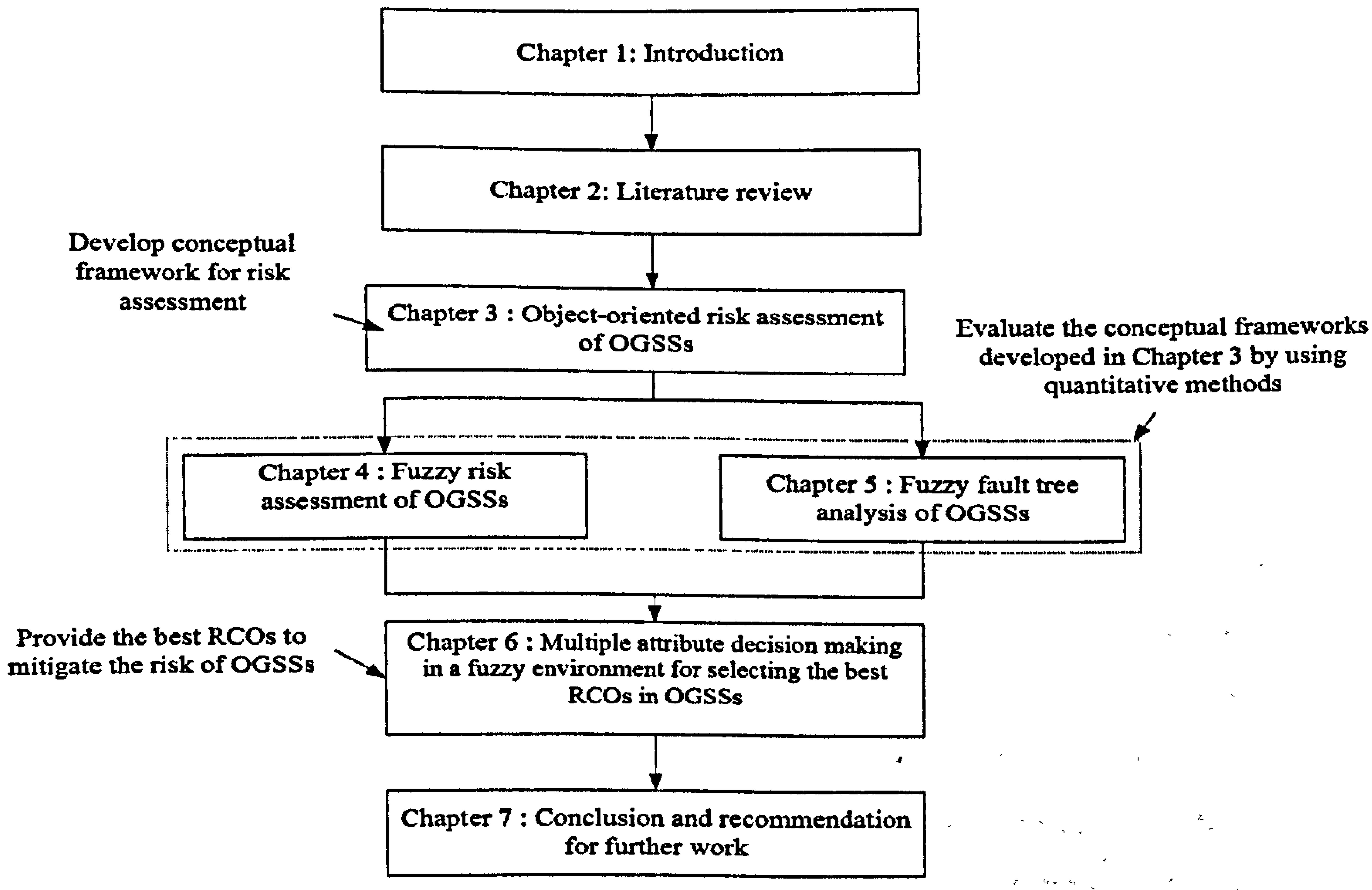


Figure 1.2 Thesis structure

Chapter 2

Literature Review

Summary

In this chapter, the current safety status of the offshore industry is reviewed. The frameworks of the safety regulations including SCR and offshore pipeline safety regulations are also discussed. The strengths and shortcomings of risk assessment techniques currently and commonly applied are examined, providing a critical review for their current practice. Finally, this PhD research is justified and discussed based on the problems and difficulties encountered.

2.1 Introduction

Offshore safety has evolved from a reactive manner towards a risk-based and goal-setting regime since 1990s. It has become an important issue in the offshore industry due to public concern following several catastrophic accidents and the introduction of safety regulations. The main objective of these safety regulations is to ensure that risks have been reduced to ALARP and RCOs to be implemented are cost-effective. In addition, due to the competitive nature, there is a need for the offshore industry to constantly conduct risk assessment and safety management with regard to assets from the initial stage, develop new approaches, propose new operational procedures and invent innovative technology. This inevitably brings new hazards and uncertainties in one form or another. Thus, risk assessment and safety management should cover all possible areas including those where traditional techniques are difficult to be applied. Accordingly, the development of a variety of novel risk modelling and decision making techniques capable of resolving such difficulties encountered is required. In this chapter, following the discussion of the current safety status of the offshore industry, the frameworks of SCR 1992 and offshore pipeline safety are presented. The strengths and difficulties of current offshore risk assessment practice encountered are subsequently discussed. Finally, the PhD research is justified with the presentation of the above difficulties.

2.2 History of offshore safety and Safety Case Regulation (SCR)

The use of structured risk management in the offshore industry began in the Norwegian Sector of the North Sea. Norwegian offshore development in the late 1970s (the Ekofisk and Frigg fields) had wellhead and production platforms separated from their accommodation platforms, linked by bridges. Several accidents in the Norwegian Sector at this time, including two on the Ekofisk field (a riser in 1975 and a blowout in 1977) demonstrated that even this arrangement involved major hazards.

The Norwegian Petroleum Directorate (NPD) issued their "Regulations Concerning Safety Related to Production and Installation" in 1976 (Vinnem, 2007). These included the requirement that if the living quarter was to be located on a platform where drilling, production or processing was taking place, a risk evaluation should be carried out. At that stage, such an evaluation would have been mainly qualitative. As part of the approval procedure for a new production platform in the Norwegian Sector, the NPD required submission of a general development plan, containing a safety evaluation of the platform concept. The NPD issued its "Guidelines for Safety Evaluation of Platform Conceptual Design" in 1981 (Vinnem, 2007). Although these were only guidelines, not regulations, they were followed very closely by Norwegian operators. The resulting studies became known as Concept Safety Evaluations (CSE). The CSE is a form of overall risk assessment of a platform, addressing the risk of impairment of safety functions. The safety functions are the escape routes, shelter areas (usually the living quarters) and the main support structure of the platform. CSEs produced a major improvement in Norwegian platforms.

In the UK sector prior to Piper Alpha, QRA tended to be applied to specific aspects of the design, rather than to overall risks. Consequently, it was mainly used as part of the detailed design when the scope for changes was limited. The Piper Alpha accident in 1988 provided tragic confutation that the major accident predictions which risk analyses had made were indeed realistic, and that QRA could be useful in trying to reduce the risks. QRA techniques were then applied to many platforms in the UK sector, as operators attempted to discover the extent of their exposure to fire and explosion hazards. The Department of Energy requested operators to re-evaluate emergency isolation arrangements for subsea pipelines and risers (the vertical sections connecting pipelines to the platform); these concentrated studies on riser hazards and the effect of installing Sub Sea Isolation Valves (SSIVs) isolate the installation from the inventory of the pipeline). QRA was found to be an appropriate tool for evaluating the relevant hazards (fire and explosion, dropped objects, valve reliability, diving risks, etc).

As a result of this activity, significant reductions of risk were achieved on many platforms by moving or installing isolation valves on risers and sub-sea pipelines by relocating accommodation in extreme cases. The effects were not confined to the UK sector, because multi-national oil companies applied similar safety evaluation to their offshore operations. Thus in the few years following the Piper Alpha accident, QRA was applied to platforms in areas as diverse as Australia, New Zealand, Malaysia, Brunei and Canada. The influential Lord Cullen Report on the Piper Alpha accident recommended a major change to a more modern system of safety regulation in the UK sector, symbolised by the transfer of responsibility to the Health & Safety Executive (HSE). Subsequently, the HSE Offshore Safety Division launched a review of all offshore safety legislations and implemented changes. The objective of this work was to seek a more goal setting regime to replace legislation which was regarded as perspective (Wang, 2002). The mainstay of the regulation is the Health and Safety at Work Act, under which a draft of the offshore installation (safety case) regulations was produced (HSE, 1991). It was then modified to incorporate the comments arising from public consultation. The regulation came into force at the end of May 1993 for new installations and November 1993 for existing installations. The regulation requires operational safety cases to be prepared for all offshore installations, including both mobile and fixed ones. In addition, all new fixed installations are required to have a design safety case in place. For mobile installations, the duty holder is owner. The SCR establishes a clear guidance as to what a safety case should include with respect to the design and operations of a particular type of offshore installation. Particular requirements to be included in a safety case for the design, operation, abandonment and well operations of different installations are also given. Installation cannot legally operate without such a safety case demonstration that has been approved by the Offshore Safety Division of HSE.

Risk criteria are standards that represent a view of regulators of how much risk is acceptable or tolerable (HSE, 1995a). A framework for decision on the tolerability of risk posed by the HSE is shown in Figure 2.1, where there are three regions, namely, intolerable, ALARP and broadly acceptable (HSE, 1995a). The risks in the intolerable region cannot be justified on any ground. In the region of ALARP, the risks must be reduced by introducing control measures towards the acceptable region. The residual risks remaining in this region will be tolerable only if further risk reduction is impracticable or its cost required is grossly disproportionate to the improvement gained. There is no need to demonstrate ALARP in the broadly acceptable region. However, it is necessary to take any measure to assure that the risks remain at this level. An accepted operational safety case must be capable of demonstrating that hazards with the potential to cause major accidents have been identified, and that associated risk have been evaluated and reduced to ALARP using appropriate measures. It is noted that since the uncertainties in input may be high the application of QRA may not always be appropriate (Wang, 2002). Therefore, the acceptance of a safety case is unlikely to rely solely on a QRA.

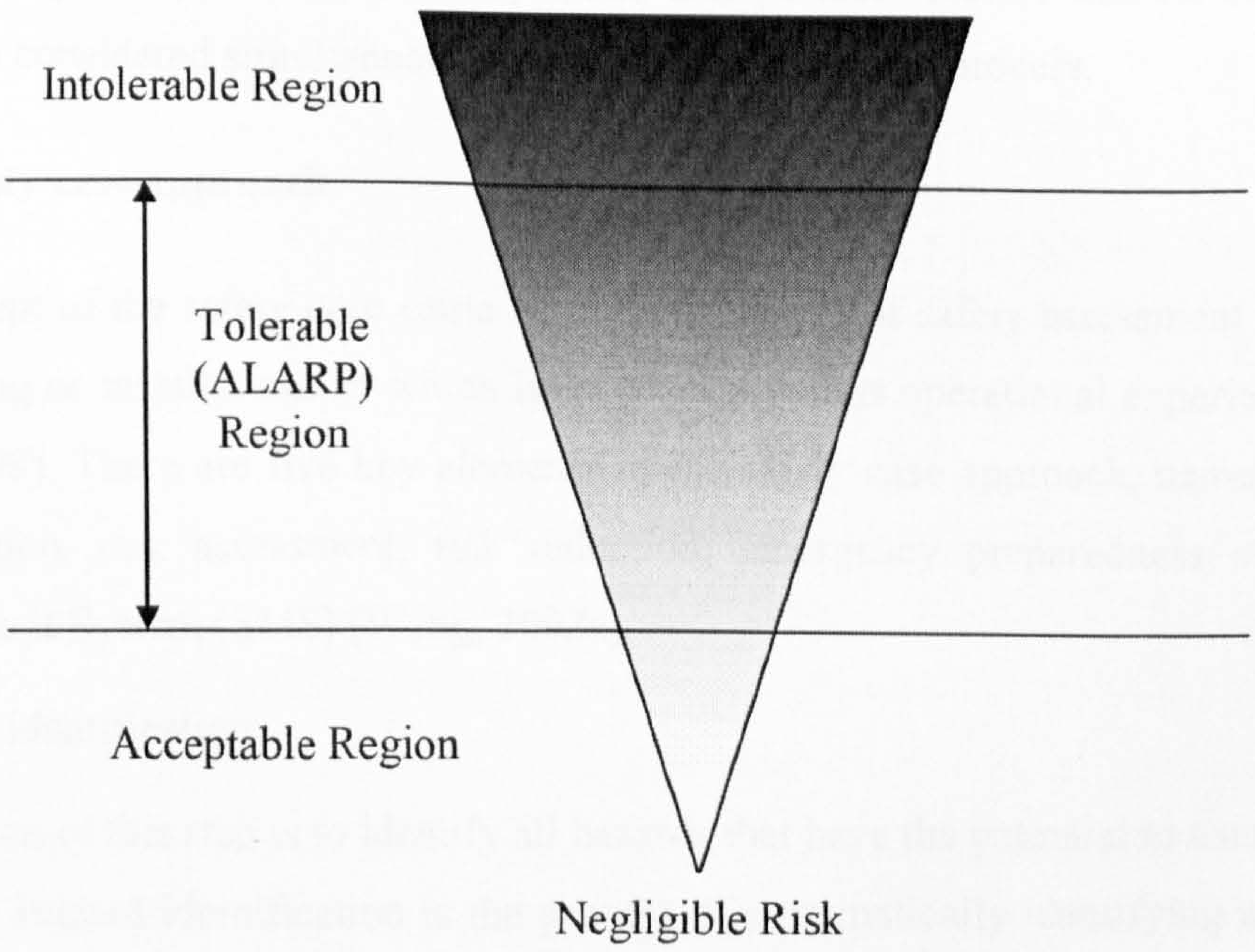


Figure 2.1 The HSE framework for decision on tolerability of risk

QRA is a relatively new technique. In general, there is lack of agreed approaches and poor circulation of data, resulting in wide variation in study quality. In some areas, accident data has not been collected or analysed, and no theoretical models are available, so that risk estimates are inevitably very crude. In other areas, availability of data and analytical techniques are being developed rapidly, and the risk estimates tend to fluctuate as a result. Because it is quantitative, QRA appears to be objective. However in reality it is very judgmental. These judgments may be explicit in situations where data is unavailable. There are also many implicit judgments in the analysis and application of available data which are often unrecognized. Overlooking the significance of these judgments may lead to false precision in the risk estimates. Over-emphasis on the judgmental nature of a QRA, on the other hand, may lead to its potential benefits being overlooked.

QRA only provides one input to decision-making about safety issues, and most of its advocates recognize that it cannot be used to make the decision itself. There are other aspects, such as public dread of particular sources of risk, which QRA does not take into account at present. Decision-making about hazardous activities is legitimately influenced by many other economic, social and political factors besides risk, which need to be considered simultaneously in the decision-making process.

2.2.1 Safety case approach

The concept of the safety case came from the principle of safety assessment of system engineering or installations in which little or no previous operational experience exists (Kuo, 1998). There are five key elements in the safety case approach, namely, hazard identification, risk assessment, risk reduction, emergency preparedness and Safety Management System (SMS) (Wang, 2002a).

1. Hazard identification

The mission of this step is to identify all hazards that have the potential to cause a major accident. Hazard identification is the process of systematically identifying all hazards and associated events that could have negative consequences. The process is also concerned with the application of brain-storming techniques conducted by trained and experienced personnel to determine the hazards. Therefore, it is often a qualitative exercise based on the expert judgement.

2. Risk assessment

Once the hazards have been identified, the associated risks will be evaluated using risk assessment techniques. The techniques employed may include qualitative, quantitative and semi-quantitative or some other risk assessment techniques such as approximate reasoning methods. It depends on circumstances encountered.

3. Risk reduction

The risk reduction measures will be identified based on the results of risk assessment obtained from Step 2. The purpose of this step is to deliver effective and practical RCOs to manage the risks. The hazards that have high probabilities of occurrence and severity consequences will have the priorities to be dealt with.

4. Emergency preparedness

The objective of this step is to ensure that the appropriate actions have been taken in the event that a hazard has become a reality so as to minimise the negative consequences caused.

5. SMS

The aim of a SMS is to demonstrate that the organisation is achieving the safety goal efficiently without jeopardising the environment. This is regarded as one of the most important factors of the safety case approach.

Conventional risk assessment methods with cost benefit approaches can be employed to prepare a safety case. The objective of incorporating the cost benefit approach into a safety case is to ensure that the measures or RCOs proposed are cost effective. This is achieved by comparing the cost of the proposed RCO with its potential benefits including risk reduction. It should be noted that significant uncertainties in the data, information and factors may be encountered in the decision making process. Therefore, there is a need to apply common sense and to ensure that any uncertainties are identified and addressed (UKOOA, 1999).

2.2.2 Relevant regulations and standards

There are several countries that have legislation for the use of QRA studies in the design and operational phases of offshore installations:

- Canada
- Australia
- Norway
- United Kingdom

The following is a brief summary of the requirements of the legislation in these countries except for the UK, which are discussed in some depth throughout this section:

1. Canada

In association with a newly developed proposal in Canada, a conceptual safety analysis is required. The field development proposal needs to define how the analysis will be met, and to state the "target level of safety" that has been defined as acceptance criteria for risk. The development proposal shall also define a "Risk Assessment Plan" which should contain a list of various specific risk and safety analyses that may be required at the detailed design stages. It should also provide a plan for the completion of these studies and analyses and an explanation of how these analyses are integrated into the design process. Finally, it should provide an explanation of the methodologies to be utilised and a discussion of their validity and relevance in the overall process.

2. Australia

The National Offshore Petroleum Safety Authority 2004 (NOPSA 2004) has issued safety case guidelines. These regulations call for safety case to be prepared for all installations and to demonstrate that risk has been reduced to an ALARP level.

3. Norway

Use of QRA studies in the Norwegian offshore industry date back to the second half of the 1970s. A few pioneer projects were conducted at that time, mainly for research and development purposes, in order to investigate whether analysis methodologies and data of sufficient sophistication and robustness were available. The next step in the development of QRA came in 1981 when Norwegian Petroleum Directorate (NPD) issued guidelines for safety evaluation of platform conceptual design (NPD, 1980). These regulations required QRA to be carried out for all new offshore installations in their conceptual design phases. NPD published a new set of regulations in 2001, which replaced the risk analysis and technical regulations from 1 January 2002. The requirement of risk analysis and other analyses were stipulated in the Health, Environment and Safety (HES) Management regulations. These regulations have requirements for analysis of risk as well as requirements for the definition of risk acceptance criteria. NPD was divided into two organisations from 1 January 2004 and the safety division of NPD was separated as a new organisation namely Petroleum Safety Authority (PSA). At the same time, PSA took over the responsibility for ensuring the safety of 6 onshore facilities in the petroleum sector, terminals and refineries. The HES management regulations were controlled by PSA. The SCRs were modified in 2005 and these revisions came into force from 5 April 2006 (Aven & Vinnem, 2007).

4. UK

The offshore regulatory regime was completely rewritten as the consequence of the Piper Alpha in 1988, based on the recommendation from the inquiry chaired by Lord Cullen (1990). The following regulations have been issued:

- SCR (HSE, 1992).
- Prevention of Fire and Explosion and Emergency Reponses Regulations (PFEERR) (HSE, 1995a).
- Management and Administration Regulations (MAR) (HSE, 1995b)
- Design and Construction Regulations (DCR) (HSE, 1996)

The PFEER regulations (HSE, 1995a) imply important requirements for active and passive safety systems, as well as emergency preparedness systems and functions. The purpose of these regulations is to ensure that protection measures against fire and explosion are used to make a risk level in the ALARP, and that sufficient arrangements are in place in order to provide a good prospect of rescue and recovery for personnel in all reasonably foreseeable situations. Operators are according to these regulations required to:

- Take measures to prevent fire and explosion and provide protection from any which does occur.
- Provide effective emergency response arrangements.

A risk based approach is recommended to deal with problems involving fire, explosion and emergency response. The need for risks to be ALARP is the basis for using a risk based design in relation to fire and explosion.

The MAR regulations (HSE, 1995b) were developed to deal with areas such as notification to the HSE of owner or operator changes or functions and powers of offshore installation managers etc (HSE, 1995b). The regulations are applied to fixed and mobile offshore installations, excluding subsea offshore installations. The importance of offshore pipeline safety has also been recognised. Pipeline Safety Regulations 1996 (PSR, 1996) were introduced to embody a single integrated, goal setting and risk based approach to regulations prescribing the safety issues to both shore and offshore pipelines (HSE, 1996a).

The SCR was amended in 1996 to incorporate verification of safety critical elements (HSE, 1996 b). Safety critical elements are the components of an installation or its plants, including computer programmes. Failure of these components may cause or contribute substantially to a major accident. Thus, the amendment objective is to prevent or mitigate the consequences. Offshore installation and wells (Design and construction, etc.) regulation 1996 (DCR, 1996) were launched to deal with various stages of life cycle of installation (HSE, 1996c). The DCR 1996 permitted the offshore operator to have a more flexibility to deal with their own safety problems. This encourages safety analysts to develop and employ novel safety assessment and decision making approaches to tackle offshore safety problems.

The offshore safety regulations, including SCR, in the UK are aimed at establishing a more goal setting regime. This is accomplished by defining specific duties of operators and setting forth high level safety objective while leaving the selection of particular hazard arrangements in the hands of operators. This is because hazards encountered by each installation may be specific subject to its unique functions and operating conditions.

2.3 Pipeline safety and regulations

Offshore pipelines operate in a physically and technically demanding environment. They are subject to severe weather, shifting sediments (especially in some areas of the Gulf), and a constant threat of corrosion. They also face seismic risks in some places. New pipelines are being installed in deeper waters, farther offshore, where the large gas and oil discoveries have been made, but where operation and maintenance present even greater challenges. The costs of inspection, maintenance and repair are also generally far greater than the ones on-shore.

The rapid growth in the number of firms operating offshore pipelines has caused some concerns, because many are new entrants who have assumed control of major operators' older and less profitable pipelines in hopes of lowering operating costs. Today there are about 170 pipeline operating companies in the Gulf, up from about 65 a decade ago by National Research Council of US (NRC, 1994). It is essential that attempts to cut costs do not interfere with adequate pipeline maintenance and safety. At the same time, all pipeline operators must contend with new regulatory costs, notably those entailed in the new standards for controlling oil pollution under the Oil Pollution Act of 1990.

Pipelines must share the seabed and waters with vessels of all types, near some of the most heavily used cargo ports and some of the most productive commercial and recreational fisheries. The potential for interference with other users was underscored in the late 1980s by two fatal accidents in which fishing boats operating in shallow waters struck inadequately buried pipelines, with ensuing explosions, injuries, and deaths (Joint task force on offshore pipelines, 1990; National Transportation Safety Board (NTSB), 1990). A more general concern is pipeline damage caused by anchors and fishing gears. Gas field service and supply boats are a particular concern near platforms, where their manoeuvring threatens pipeline risers and their anchoring can damage pipelines on the seabed. In addition, hurricanes, mudslides and other natural forces can also damage pipelines or cause them to fail. Hydrocarbon spills from storms can be limited by shutting down and evacuating the platforms and pipelines.

The ongoing shift of production to deeper waters will increase the need for attention to safety. Much of the existing offshore pipeline infrastructure, and particularly the transmission pipelines, will remain in service, carrying hydrocarbons from the new deeper fields. Deep water pipelines are relatively inaccessible to workers, and they operate at low temperatures, which encourage the formation of corrosive brines, ice like gas hydrates and waxes. As a result, inspection and maintenance problems will require new and innovative solutions.

These trends have led the industry and its safety regulators to re-examine their approaches to ensuring safety. They are asking fundamental questions (NRC, 1994):

- What are the risks, and are they growing?
- Is maintenance technology keeping pace with the aging of the pipelines?
- Are today's inspections and repair techniques suitable for the new deep water pipelines?
- Are the measures taken to avoid interactions of pipelines with fishing vessels, cargo vessels, offshore supply and service boats, and recreational boats adequate?
- Do hydrocarbon spill prevention and response requirements harmonize with the regulations to ensure personnel safety and protection of property?
- Do the industry and its regulators collect the right data to support decisions about risk abatement?

The hazards presented by offshore pipelines are not to be taken lightly; resulting in environmental and property damage, human injury and death. Vessels manoeuvring in shallow water may dent or rupture pipelines, releasing explosive or environmentally damaging hydrocarbons. In deeper water, fishing vessels sometimes snag nets and other gear on valves and other pipeline features, tearing the nets and occasionally causing leaks. Larger vessels may drag their anchors across pipelines, bending or cracking them. Internal and external corrosions are pervasive threats of leaks. Storms and seafloor mudslides may move, damage, or expose once-buried pipelines, allowing anchors and nets to foul them. Objects dropped from vessels or platforms can also damage pipelines. During the late 1980s the 17,000 miles of pipeline in the waters of the U.S. Outer Continental Shelf (USOCS) experienced a leak or other reportable failures about once every five days, owing to one or another of aforementioned causes (Woodson, 1991).

Injury or loss of life as a result of pipeline damage is rare, but not unknown, and it is these risks that are perhaps most prominent in the public mind. Natural gas and natural gas liquid pipelines in particular (about 70 percent of the marine pipeline mileages) hold the potential for explosions. A series of dramatic accidents in the late 1980s, involving natural gas explosions associated with pipeline damage, resulted in deaths, injuries, and substantial property damage.

The Sea Chief accident. In July 1987, while working in shallow coastal waters off Louisiana, the menhaden purse seiner *Sea Chief* struck and ruptured an 8-inch natural gas liquids pipeline operating at 480 psi. The resulting explosion killed two crew members. Divers investigation found that the pipe, installed in 1968, was covered with only 6 inches of soft mud, having lost its original 3-foot cover of sediments.

The Northumberland accident. October 1989 saw a strikingly similar accident, with even greater consequences. The menhaden vessel *Northumberland* struck a 16-inch gas pipeline in shallow water near Sabine Pass, Texas. The vessel was engulfed in flames; 11 of the 14 crew members died. The pipeline, installed in 1974 with 8 to 10 feet of cover, was found to be lying on the bottom, with no cover at all (NTSB, 1990).

Sonat/Arco, South Pass 60. In March 1989 a flash fire and explosion occurred on a Sonat/Arco platform in lease block South Pass 60, during repair of an associated pipeline. Seven of the platform crew died, and ten others were injured. Property damage was estimated about $70 million. The investigation showed that the incident had been caused by human error, leading to the sudden release of gas and liquids from the pipeline cut during repair work (which had been occasioned by damage from an anchor line). The repair was complicated by the operator's failure to update pipeline drawings, which left the workers unaware of a subsea valve assembly that would have made the repair easier and safer (U.S. Department of Transportation, 1989).

Reported causes of pipeline failures are not reliable; they are often determined by guesswork, without complete investigation or repair. Follow-up or "supplemental" reports are sometimes not made (U.S. Department of Transportation, 1989). In addition, different categories of causes cannot be regarded as entirely distinct, because of the likelihood of multiple failure modes. For example, a corrosion-weakened pipeline ruptured by storm or anchor damage would generally be reported as failure due to storm or anchor damage, not corrosion. Causes of failures are categorized differently by the three analysts (Table 2.1). For comparison, they can be divided into the following broad categories:

- Corrosion (external and internal).
- Maritime activities (anchors, nets, trawls, and vessel contact).
- Natural forces (storms, hurricanes, and mudslides).
- Material failure.
- Other unknown.

Table 2.1 Causes of offshore pipeline incidents (NTSB, 1990)

Cause of failure	Woodson (Mineral Management Service (MMS) data, 1970-1990)	Mandke (Mineral Management Service (MMS) data, 1970-1990)	Broussard (Office of Pipeline Safety (OPS) data, 1984-1990)
Corrosion (Internal and external)	50% (456)	50% (343)	45% (114)
Maritime activities (nets, vessel contact and etc.)	14% (124)	21% (138)	-
Natural force (mudslide, storms and etc.)	12% (106)	12% (82)	31% (78)
Material failure	10% (94)	9% (63)	14% (36)
Others	15% (136)	9% (63)	10% (24)
Total	100% (916)	100% (690)	100% (252)

Corrosion is the most likely cause leading to pipeline incidents. In Woodson's analysis in Table 2.1, for example, corrosion is the most widely reported cause of failure (50 percent of the incidents whose cause is reported), followed by maritime activities (anchor and net damage and vessel collisions) at 14 percent and natural forces (storms and mudslides) at 12 percent.

It is impossible to draw firm conclusions about the relative roles of internal and external corrosion, because more than one-third of the corrosion failure reports do not specify the location of corrosion. Mandke's (1990) analysis showed that about 70 percent of corrosion failures occurred in lines of 10 inches or less in diameter, and that 78 percent took place at platforms, either in risers (vertical pipeline extensions from the seabed to the surface) or on the adjacent seabed. Industrial experience suggests that many of these failures occur in production flow lines, in risers (through external corrosion in the splash zone or under clamps), and at the pipe bend where the riser meets the seabed (through internal corrosion on the pipe bottom) (Mandke's, 1990). However, the data is insufficient to establish these patterns without doubt. Analysis of offshore pipeline incidents is extremely difficult, due to the inconsistency of data collection by the various agencies without a shared focus on safety planning in data collection.

The lack of consistent and comprehensive data on the safety record of offshore pipelines is a severe challenge for safety planning. Several public agencies that regulate the industry have varied missions. Their individual efforts to investigate failures have not led to the development of a comprehensive safety data base. Data is collected inconsistently, without a well-thought-out or coordinated plan, and without a consistent focus on safety planning. Reports are often incomplete or inconclusive. Risk assessment and safety management on the basis of such limited information is challenging, but not impossible. Modern techniques of risk analysis can guide the industry and its regulators in setting risk assessment and safety management priorities. Some of these techniques are outlined in this research, along with the framework of a risk analysis approach that could be applied to the offshore pipeline industry.

Risk assessment and safety management has been widely developed by both governments and operators of gas pipeline systems. In the United States, an executive order 13010 establishing the President's commission on critical infrastructure protection was issued on 15 July 1996. This order developed a national strategy for protecting infrastructure from various threats in order to assure their continued operation (Clinton, 1996). In President's commission on critical infrastructure protection, a gas pipeline system is considered as one of the critical infrastructures. In May 1998, a Presidential Decision Directive 63 (PDD63) was issued to call for a national effort and assure the security of the increasingly vulnerable and interconnected infrastructures in the USA (Clinton, 1998). The U.S. Department of Energy established the Office of Energy Assurance (OEA) to direct the department's activities in accordance with (PDD-63) and the priorities established by the Secretary of Energy. From May 1998 to September 2001, a team of experts was established to work within the energy industry (electric power, oil, and natural gas), and perform a series of vulnerability assessments as part of OEA's vulnerability assessment and survey program (OEA, 2001). The goal of such an assessment is to help the organizations in the energy-sector to identify and understand the existing threats and the vulnerabilities (physical and cyber) exposed to the infrastructure, and to stimulate actions to mitigate those with severe consequences.

In the UK, "A Guide to Risk Assessment and Risk Management for Environmental Protection" and "Guidelines for Environmental Risk Assessment and Management" were published in 1995 and 2000 respectively. They suggested risk assessment and management as essential elements of structured decision making processes across the government (DETR, 1995; DETR et al, 2000). The guidelines set out some basic principles which the Department of the Environment, Transport and the Regions (DETR) and Environmental Agency (EA) would normally intend to use in the assessment and management of risks and which are recommended for all public-domain risk assessments (DETR et al, 2000). They also provided decision makers, practitioners and the public with a consistent language for risk assessment.

In risk management of pipelines, QRA was not common among most EU countries (Papadakis, 2000). By tradition, standards and design rules applied to pipelines were "deterministic" in their approach, to ensure safe operation without explicit reference to risk assessment. Risk assessment emerged as an important engineering discipline in some Australian states (including WA) and American states (Parfomak, 2007). For example, the Pipeline Committee of Standard Australia (ME/38), was incorporated in AS2885 (part 1 issue 1997), a uniform risk methodology (DOCEP, 2006) for risk estimation of hydrocarbon pipelines. A qualitative approach was used in this standard, whereby threats to pipeline integrity were systematically identified and corresponding risks could be assessed throughout the entire length. Qualitative methods are used first of all in the verification of concordance of safety level with valid principle contained in legal regulations and standards. These rules usually refer to separate devices and represent the minimum requirements that must be satisfied to reach an acceptable safety level. The aim of risk analysis and safety management is to use the data and information that is available or readily attainable to make decisions about using resources in the most effective way to enhance pipeline safety.

2.4 Risk assessment techniques

Risk assessment has been part of decision analysis since human was able to reason. However, the formalised process of making decisions about risk was formed much later and began with probability theory. Probability is a way of expressing knowledge or belief that an event will occur or has occurred. In mathematics the concept has been given an exact meaning in probability theory, that is used extensively in such areas of study as mathematics, statistics, finance, gambling, science, and philosophy to draw conclusions about the likelihood of potential events and the underlying mechanics of complex systems. Aside from some elementary considerations made by Girolamo Cardano in the 16th century, the doctrine of probabilities dates to the correspondence of Pierre de Fermat & Blaise Pascal (1654), Christiaan Huygens (1657) gave the earliest known scientific treatment of the subject (Garrick et al., 2004).

The widespread, fromal application of probablistic risk assessment to critical infrastructure began in the earliest in the late 1900s. Some typical safety analysis techniques developed and applied in that period include: the Risk Matrix Method (RMM) (Halebsky, 1989; Tummala & Lenug, 1995), Preliminary Hazard Analysis (PHA) (Military standard, 1999; Henely & Kumamoto, 1992), What if analysis (Pillay and Wang, 2003a), HAZard Operability (HAZOP) studies (Bendixen et al., 1984), FTA (Ang & Tang, 1984), Event Tree Analysis (ETA) (Henley & Kumamoto, 1992), Markov Chains (MCs) (Norris, 1998), Failure Mode, Effects and Criticality Analysis (FMECA) (Andrews & Moss, 2002), etc. With the further development of the probability theory in risk asessment, many had indicated that the applications in the behavior based or management based fileds were more possibilisstic than probablistic, more experience than analytical based and more qualitative than quantitative (Yang, 2006). It has been stated that safety anlysis can be generally divided into two broad categories namely quantitative and qualitative analysis (Wang & Ruxton, 1998). Historical casualty data and information play an important role in safety analysis. If historical data is avaialble, quantitative method can be employed to perform analysis.

FTA and ETA are the most widely used modelling methods for risk analysis. A fault tree is a logic diagram presenting the casual relationship between events which indiviually or collectively contribute to occurrence of a higher level event. Thus, the probability of occurence of a specific hazard can be determined. In addition, FTA is capable of considering common cause failures in systems with redundant or standby elements. It also has the capability of contemplating failure events or causes related to human errors. FTA is a top down approach, systemically considering the causes or events at levels below the top level. Prior to the use of quantitative FTA, the probability of occurrence of each basic event has to be obtained. If two or more need to occur to cause the next higher level event simultaneously, a logic AND gate is employed to express the operation. If any of two or more lower level events can cause the next higher level event directly, an OR gate is applied to demonstrate such an operation. The logic gates determine the addition or multiplication of probabilities to obtain the values for the Top Event (TE).

An event tree is a logic diagram applied to analyse the effects of unintended events. Such a technique first expresses the probability or frequency of an accident linked to the safeguard measures required to be implemented to mitigate or prevent escalation after the occurrence of the event. Success and failure paths lead to various consequences with different magnitudes. The liklihood of each consequence is finally obtained by multiplying the probability of occurrence of the accident by liklihood of failure or success in each path.

As aformentioned, historical data is crucial for risk assessment. In theory, the reliability of the result obtained depends upon the data collected. Therefore, it is highly likley that the risk analysis techniques previously discussed will produce a reliable outcome if the data in hand is complete.

However, such techniques may not be practicable in circumstances where the lack of data exists or the level of uncetainty associated with failure data may be unreasonably high (Wang et al., 2004). This is particulary true for large offshore systems at the intial design stages or newly adopted processes. Only non-numerical data, which could be subjective may be applied at such satges. To sum up, the problems encountered by risk assessment researchers due to the nature of offshore operations may include (Wang et al, 2004):

1. Inadequacy of historical data related to many newly adopted processes and regulations for wells, pipelines and for many novel designs. In many cases the staitstical accuracy of this inadequate and limited data avaialbe for safety analysts may be poor.

2. It may be difficult to quantify the probabilities of occurrence and consequences of hazards. This is because those hazards are associated with the operational process in a very changeable enviroment and therefore it may involve a high level of uncertainty.

3. A large number of assumptions, judgments and opinions are involved subjectively in a risk quantification process. As such, considerable skills are required for safety analysts to interpret the results produced.

4. It may be impracticable for all scale experimentations to be conducted due to a high level of cost. The use of computer simulation may be potentially possible.

The unavailability and incompleteness of data can lead to uncertainty, in particular for novel offshore systems or safety processes at their initial design and operational stages. Uncertainty is defined as a function in which a person does not have appropriate quantitative and qualitative information to prescribe or predict deterministically and numerically a system and its behaviour or other characteristics. According to the work by Ang & Tang (1984), there is uncertainty in all engineering-based systems because these systems rely on the modelling of physical phenomena that are either inherently random or difficult to model with a high degree of accuracy.

Methods for analysing and describing uncertainty can range from simple to complex depending on circumstances encountered. Common approaches applied to handle uncertainty can be divided into two different categories: those developed based on probabilistic analysis, including classical set theory, probability theory and Bayes theory; and those based on possibilistic analysis, including possibility theory and fuzzy set theory (Eleye-Datubo, 2006). The uncertainty modelled by the methods under the first category is represented by a collection of estimates of the quantity and degree of certainty or uncertainty measured by means of the distribution values in the collection of such estimates. The methods falling in the second category are reasoned with an epistemic state using max/min calculus that is not found in the probability theory. Among approaches under the category of possibilistic analysis, the significance of fuzzy set theory is the use of linguistic variables capable of providing a flexible modelling of imprecise data and information. The other factor, as important as uncertainty, is complexity of risk assessment. The complexity of pipeline systems mainly arises from the composition of a large number of components and subsystems which, in turn, consist of further sub-subsystems or sub-components. The exact definition of components and sub-components depends on the level of details of the required analysis and the level of available data (Mays, 2004b). This introduces difficulties in establishing cause-effect relationships for specific risks in offshore pipeline systems. Therefore, both knowledge of components and their relationships are important for a thorough understanding of the operation of the overall system. A risk assessment would be effective and comprehensive if it could be consistently performed at both the component and the overall system levels. However, this is hard to achieve by the existing methods as they usually focus on one specific part of an offshore pipeline system.

FMECA, HAZOP, What if analysis and PHA are qualitative methods. As previously mentioned, the aim of this research is to perform quantitative analysis of OGSS. Therefore, the aforementioned methods are not suitable for this research project. FTA, ETA and MC can be used for quantitative analysis. However, they may not be applicable in circumstances where the lack of data exists. Fuzzy set theory is combined with FTA for solving the issue. Therefore, Fuzzy FTA is tailored for performing quantitative risk assessment of this research project. Table 2.2 provide the advantage and disadvantage of all the mentioned risk assessment techniques.

Table 2.2 Advantages and disadvantages of risk assessment methods

Risk assessment methods	Advantages	Disadvantages
FMECA	1. It is a very structured and reliable method for evaluating reliability of systems 2. The concept and application are easy to learn	1. The approach is not suitable for multiple failures 2. It can not be applied for quantitative risk assessment
HAZOP	1. This method covers human errors 2. It utilizes operational experience 3. This method is very suitable for operational stages	1. It is a time consuming method 2. It dose not consider dependency between hazards 3. It can not be used for quantitative assessment
PHA	1. This method helps to ensure that the system is safe 2. This method is very suitable for design stages	1. The effects of interactions between hazards are not considered 2. This method is not suitable for quantitative assessment
FTA	1. This method identifies all the possible causes of a specified undesired event 2. It can be applied for operational and design stages 3. It suitable for quantitative risk assessment	1. This method is not able to calculate the probability of TE and importance of all possible causes in the presence of data shortage 2. It is not suitable for modelling dynamic scenarios
FFTA	1. This method identifies all the possible causes of a specified undesired event 2. It can be applied for operational and design stages 3. It suitable for quantitative risk assessment 4. This method can solve the issue of data shortage	1. It is not consider dependencies between hazards in fault tree

2.5 Decision-making context

The types of decisions and their related decision-making processes vary a lot between different sectors and levels in business organizations. One should consider the whole decision cycle including the various decision activities to understand this problem area (Power, 2002).

The four typical decision elements are:

1. Goals and relevant alternatives.

2. Ranking of alternatives.

3. Decision environment.

4. Decision makers.

2.5.1 Goals and ranking alternatives

The first two elements above contain the basic elements of a decision situation. In addition to the clearly stated goals the alternatives or decision options are being limited and defined to a comparable level. The following sections deal with the last three elements in the above list. The description has been prepared on a general basis.

2.5.2 Ranking alternatives

A sequential decision process model, or a decision loop, is illustrated in Figure 2.2. The decision process typically consists of the following seven basic steps (Marakas, 2003):

1. Define the problem.

2. Decide who should decide.

3. Collect information.

4. Identify and evaluate alternatives.

5. Decide.

6. Implement.

7. Follow-up and assess.

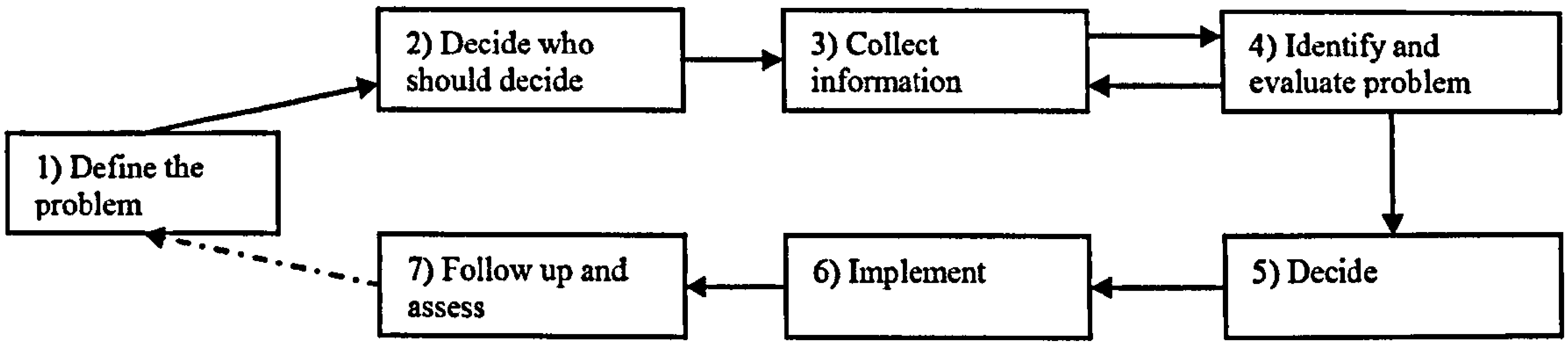


Figure 2.2 A general decision process model

1. Define the problem

A well-defined problem is of great importance for the quality of decisions. If the problem is wrongly or not thoroughly defined, it may be impossible to make a decision. The complexity of many organizations sometimes makes it hard to identify the "real" problem. A typical confusion is not to distinguish between the symptoms of the problem and the problem itself. A symptom is evidence of a problem but not necessarily the problem itself (Marakas, 2003).

A number of tools and actions may assist in problem identification. Diagnosis is the identification of problems or opportunities for improvement in the current decision-making behaviour. Diagnosis involves determining how decisions are currently made, specifying how decisions should be made, and understanding why decisions are not made as they should be. Diagnosis of problems in a decision process involves completing the following three activities (Marakas, 2003):

- Collect data on current decision-making using techniques such as interviews, observations, questionnaires and historical records.
- Establish a coherent description of the current decision process.
- Specify a norm for how decisions should be made to improve decision-making in the future.

2. Decide who should decide

A decision process can be categorised according to the degree of involvement and engagement of individuals. The three categories are an autocratic, a consultative, or a group decision process (Power, 2002). Individual decision makers make decisions by themselves in an autocratic way with the available information. Finally, a group decision process is characterised as participative by involving members of the group in the decision-making itself. Criteria for choosing an autocratic, a consultative, or a group decision process are (Power, 2002):

- The need for acceptance of the decision.
- The adequacy of available information.
- The subordinate acceptance of organizational goals.
- The likelihood of a conflict situation regarding a preferred solution.

3. Collect information

Information is collected based on a definition of the factors that affect the problem together with the viable alternatives. The cost of collecting data must always be weighed against the expected benefits. The information systems available may provide the relevant information for decision-making in an effective manner at an acceptable cost.

4. Identify and evaluate alternatives

The most creative part of decision-making is the identification of the set of alternatives and determining what criteria should be used in the evaluation of options.

5. Decide

Making a decision is to commit to a course of action or inaction. In some situations, a decision must be made if it is required or demanded by circumstances, customers, or stakeholders. Decisions are then sometimes made with less information than one would like, and with some feasible alternatives not properly evaluated or considered. In these situations no decision may be taken pending on more information to be collected. A Decision Support System (DSS) may potentially reduce procrastination and indecision by helping to structure the decision situation and to gather the necessary information more easily. DSS may help to weight and structure qualitative criteria, like company impact, reaction of competitors, and general reputation. Most of the focus in this section deals with topics related to the decision-step in the general decision process model, as shown in Figure 2.2.

6. Implement

A decision or choice among alternatives is the culmination of one specific decision process. DSS may help communicate decisions, monitor plans and actions, and track performance.

7. Follow-up and assess

Because situations do not remain the same for a long time, managers are often dealing with problems that grew out of solutions chosen for previous problems. The completion of one decision loop may lead to consciousness about new problems based on the original problem definition. DSS helps in monitoring, following-up, and assessing such consequences as well.

2.5.3 Decision environment

The decision environment may be both internal and external. Factors in the internal environment influencing decisions include (Marakas, 2003):

1) People, and their goals, experience, capabilities, and commitments.

2) Functional units, including the technological characteristics, independence, interdependence, and conflict among units.

3) Organization factors, including goal and objectives, processes and procedures, and the nature of the product or service.

External decision environmental factors may be laws and regulations, and demands from external stakeholders.

2.5.4 Decision makers

Different types of decision makers need support that is adapted to their problem contexts. The classification of decision makers has been utilised (Murphy et al., 1999):

- Individual decision maker.
- Multiple decision makers.
- Group decision maker.
- Team decision maker.

The individual decision maker stands alone in the final decision process. The decision rests on his/her unique characteristics with regard to knowledge, skill set, experience, etc., and individual biases come to bear in the decision process.

Multiple decision makers comprise several people interacting to reach a decision. Each member may come with a unique motivation or goal and may approach the decision process from different angles. They do not necessarily meet in a formalised manner to conduct discussions as a unit. In contrast, a group decision maker is characterised by membership in a more formal structure where members of the group share similar interests in the decision outcome. Each member is involved in the making of a decision based on consensus of the group, but none possesses any more input or authority to make the decision than any of the others.

The team decision maker is a combination of the individual and group classification. The team produces the final decision, but the formalization of that decision and authority makes it rest with an individual decision maker. The decision support may come from several individuals empowered by the key individual decision maker to collect information. In this context the team produces the final decision, but the authority to make it rests with the individual team leader.

2.5.5 Categorization of decisions

Decisions may be categorised according to the level of certainty of each decision outcome. The following categories may be used:

- Decision under certainty.
- Decision under uncertainty.

2.5.5.1 Decisions under certainty

Decisions under certainty mean that the decision maker has perfect knowledge about the alternatives and their typical outcomes (Hitt et al., 1983). Such decisions are the simplest for a manager to make, but are quite rare. This category is of minor relevance to the current problem context because most of the decisions in marine and offshore engineering are taken under risk and uncertainty, without a perfect knowledge.

2.5.5.2 Decisions under uncertainty

Decisions made under conditions of uncertainty are the most common types for managers. Sometimes there is not enough information to estimate the probability of the potential outcomes. Thus, it is termed as a decision under uncertainty. In well engineering the potential outcomes from main decisions are typically known, but the probabilities are not. Uncertainty is then related to the restricted information or lack of information on which to base the analyses or to reliably estimate the probabilities of known outcomes (Hitt et al., 1983). Another interpretation of uncertainty also involves the utility as a measure of the desirability of outcomes or otherwise the consequences of decisions. The decision elements, probability and utility are related dually. In a sense, the probability element is a function of our information at any given time and utility element is an expression of our preferences are both subjective (Jordaan, 2005). Decisions made under uncertainty are perhaps the most difficult of all decision situations.

Hwang & Yoon (1981) proposed the TOPSIS method which is a multiple criteria method to identify the best solution from a finite set of points. TOPSIS is one of the effective methods and it is also widely accepted multi-attribute decision-making technique due to its sound logic simultaneous consideration of the positive-ideal and the negative-ideal solutions and easily programmable computation procedure. The basic principle is that the chosen points should have the "shortest" distance from the positive ideal solution and the "farthest" distance from the negative ideal solution. The advantages for TOPSIS include (a) rationally comprehensible concept, (b) good computational efficiency, (c) ability to measure the relative performance for each alternative in a simple mathematical form (Yeh, 2002). In the traditional TOPSIS model, the measurement of weights and qualitative attributes did not consider the uncertainty associated with the mapping of human perception to a number (Makridakis et al., 1983). The concept of applying fuzzy numbers to TOPSIS was first suggested by Chen & Hwang (1992), but their fuzzy TOPSIS algorithms are incomplete. The main steps of multiple criteria-attribute (complex) decision-making are as follows:

a) Establishing system evaluation criteria that relate system capabilities to goals.

b) Developing alternative systems for attaining the goals (generating alternative).

c) Evaluating alternatives in terms of criteria (the values of the criterion functions).

d) Applying a normative multi-criteria analysis method.

e) Accepting one point as "optimal".

f) If the final solution is not accepted, gather new information and go into the next iteration of multi-criteria decision-making.

Steps (a) and (e) are performed at the upper level, where decision makers have the central role, and the others are mostly engineering tasks. For step (d) a decision maker should express her/his idea about importance of criteria to determining their weights. These weights do not have clear economic significance, but they match model with actual concepts of decision making. By considering this fact that in many cases determining precisely the exact value of the attribute with respect to criteria is difficult, their values are considered as fuzzy data. Therefore the concept of TOPSIS is extended to solving problems under uncertainty.

2.6 Conclusion and discussion

In order to ensure the origination of the study, this chapter gives a comprehensive literature review associated with risk assessment of offshore pipeline systems. It emphasizes the explanation of applying uncertainty treatment methods and techniques to risk assessment and decision making in previous studies. The offshore industry has been moving towards a risk-based and goal-setting regime since the 1990s. Traditional risk assessment techniques such as FTA and ETA are capable of providing results with confidence if historical data are available. However, they may not be applicable in circumstances where the lack of data exists or the information available consists of high level of uncertainty. Therefore, risk analysis in such circumstances strongly relies on human judgement. Different techniques including AHP, Evidential Reasoning (ER) and FTA can be incorporated respectively into risk assessment and fault tree frameworks with fuzzy set theory to facilitate the analysis performance and provide results with confidence. In a decision making process, many factors need to be considered when evaluating the RCOs for an OGSS. Under such circumstances where the factors considered have different attributes, the best RCOs will be identified using the FTOPSIS approach. The objective of this PhD research is to establish a platform of risk assessment and safety management consisting of various frameworks addressing OGSS safety without jeopardising the efficiency of OGSS operations under circumstances where the lack of data exists or high level of uncertainty is presented.

Chapter 3

Object Oriented Approach of OGSSs

Summary

Frameworks of risk assessment are developed in this chapter based on the concept of OOA and characteristics of OGSSs. Object-oriented hierarchy is developed to represent the relationships among components, subsystems, and the overall system. Furthermore, for a component at the lowest level in the hierarchical structure, an object state transition diagram describes the objects state due to influence of hazards. It is proposed that two frameworks are developed for risk assessment using an object oriented structure and object transition diagrams. The former framework will be used in conducting an aggregative risk assessment whilst the latter will be used in the FTA.

3.1 Introduction

Frameworks of risk assessment are developed in this chapter based on the concepts of an OOA and the characteristics of OGSSs. Firstly, Section 3.2 introduces the basic concepts of OOA and their potential in dealing with the complexity of OGSSs. Then in Section 3.3, an object-oriented hierarchy is developed to represent the relationships among components, subsystems, and the overall OGSS. Furthermore, for the components at the lowest level in the hierarchical structure, object state transition diagrams are used to describe the state transitions due to the influences of multiple hazards and threats. Two kinds of frameworks are developed for risk assessment on the basis of the above object-oriented structure and object state transition diagrams. One is for aggregative risk assessment which is discussed in Section 3.4; and the other is for FTA and discussed in Section 3.5. Aggregative risk assessment is to analyse the risk levels of different objects in an OGSS, i.e., a component, a subsystem and the overall system. While fault trees are used to describe the cause-effect relationships for a given risk in the system, these frameworks are developed at both the component and system levels in order to meet the requirements of a comprehensive risk assessment.

3.2 OOA

3.2.1 Basics concepts

OOA is a method that can naturally represent real-world entities and phenomena in terms of objects and classes (Booch, 1994; Martin & Odell, 1994; Embley, 1992). In an object-oriented modelling paradigm, object and class are two key concepts with which analysts can effectively manage complex engineering systems. These two concepts are also effective to organise risk information in an OGSS.

3.2.2 Objects

Objects are models which can be used for representing real-world entities with the capability of communicating with one another (Booch, 1994; Martin & Odell, 1994). This communication consists of messages exchanged between objects. Messages represent the transfer of information, materials, or energy. Components (e.g., pipe, pump, etc.) and subsystems (e.g., gas source, gas distribution, etc) in an OGSS can be viewed as different objects. These objects are interconnected to form a system of supplying gas to consumers. Gas flow is the message exchanged between any two objects in an OGSS.

When an object receives a message, it gives responses by altering its internal state and important characteristics or attributes, and generating output messages to other objects in the model. The way in which the object responds to messages depends on its internal processes and states.

One of the most important characteristics of objects is encapsulation. This means that the attributes and behaviours of a component or subsystem are entirely encapsulated within the confines of a self-contained object. Attributes define an object's state and behaviours describe an object's functionality. The entire system is thus viewed as the combination of individual objects with different functionalities. Meanwhile the individual objects communicate with one another in a way that faithfully replicates their interactions in the real-world (Booch, 1994). In an OGSS, for example, a well can be viewed as an individual object encapsulating the attributes of natural gas. A gas refinery can be viewed as an another object which encapsulates the behaviour of removing the impurities from natural gas in order to meet the standards specified by the major pipeline transmission and distribution companies. Similarly, a pipe in the gas system can be viewed as an object which encapsulates the attributes, such as length, diameter, age, and roughness factor, and behaviour of delivering gas. The overall OGSS is thus a composite object composed of interconnected individual objects (including well, gas refinery, pipes, etc.). Figure 3.1 demonstrates an OGSS with its objects.

3.2.3 Classes

In a real engineering system, there are many objects of a specific kind. It would be extremely inefficient to repeat the use of the same methods in defining every single occurrence of that object. Thus the concept of class is proposed in the object-oriented approach. A class is a template or blueprint that defines the methods and variables included in a particular kind of object (Booch, 1994; Martin & Odell, 1994). The methods and variables that make up the object are defined only once in the definition of the class. The objects that belong to a class are called instances of the class which contain only their own particular values for the variables. This concept is also applied to a gas pipeline network with large numbers of pipes (Lewandowski, 1994). This process of obtaining classes is usually called generalisation in practice. Even though it is only an abstract concept which has no physical counterpart in real world, class plays important roles in helping people organise complex information in the system.

Inheritance is an important characteristic of class. It is one of the fundamental rules supporting abstraction and generalisation in the OOA. Two types of class are introduced in generalisation process, one is called base class and the other is derived or instance class. Inheritance allows the derived class or instance to inherit the attributes and behaviours defined within the base class. In a distribution network, pipe instances are usually viewed as derived classes, and the general pipe class is viewed as their base class. Attributes (i.e., diameter, length, age, material, roughness coefficient, etc.) and behaviours (i.e., deteriorating with time, delivering gas, etc.) are defined within the base class. These attributes and behaviours are inherited by the pipe instances. This mechanism of inheritance facilitates the process of risk assessment in an OGSS by developing common risk models for pipe class, while repeatedly reusing these models in different pipe instances.

3.2.4 Applications of OOA

Applications of an OOA have covered various areas in practice. An object-oriented paradigm has represented a major achievement in software engineering that facilitates modelling complex real-world problems (Martin & Odell, 1994). When properly applied, it can yield robust models consisting of reusable and easy to maintain components in different kinds of engineering systems (Booch, 1994; Solomatine, 1996; Ross et al, 1992; Black & Megabit, 1995). Meanwhile, OOA has also been used to solve engineering problems, which includes development of framework for decision making (Liu & Stewart, 2003), modelling of natural gas pipeline networks (Lewandowski, 1994), surface water quality management (Elshorbagy & Ormsbee, 2006), management of river system and water resources (McKinney & Cai, 2002; Simonovic, et al., 1997; Reitsma & Carron, 1997; Tisdale, 1996), reliability and risk assessment (Wyss, et al., 2004; Wyss & Duran, 2002; Black & Megabit, 1995; Matsinos, et al., 1994), material failures (Roberge, 1996), uncertainty modelling of early design (Crossland, et al., 2003) etc. The effectiveness of using the OOA to deal with the complexity of systems has also been specifically illustrated by many researchers (Booch, 1994; Weber & Jouffe, 2006).

However, its potential in risk assessment of complex systems has not been investigated to a significant degree in the previous research. From the above discussion on applications of an OOA, it is identified that one of most important powers of objects and classes is their effectiveness in organising complicated information of engineering systems (Martin & Odell, 1994). Firstly, all engineering systems including OGSSs are designed, constructed, operated and managed in terms of objects. For an OGSS, its performance is determined by the performance of the consistent components or objects. As a result, individual objects contribute to the one of the overall OGSS. Secondly, most of the knowledge about the engineering system focuses on objects. For example, many models (including physical and statistical models) have been developed to represent the deteriorating process of gas pipes with time. Even though these models are different with their applications, they are all related to specific pipe objects in a gas system. These models can be viewed as the behaviours or methods of pipe objects. Thirdly, generalisation of classes is a straightforward way to avoid repeated work, which thus makes it effective to manage the common features in a complex system. The above discussion shows the possibility of using an OOA as an effective tool to organise complex risk information in OGSSs. Such awareness motivates this study to adopt an OOA to develop frameworks of risk assessment.

3.2.5 Complexity of OGSSs and OOA

Since complexity is one of the hurdles limiting the application of conventional risk assessment methods, it is necessary to explicitly discuss the potential of an OOA in dealing with complexity of the OGSS. In order to effectively analyse complex systems, many researchers have carried out extensive studies on the characteristics of complex systems. Courtois (1985) suggested five attributes common to all complex systems on the of the work of simons (1982). Such five attributes are mentioned in the following parts. The characteristics of the OOA make it possible to deal with the complexities effectively. Being one of the complex engineering systems, a general OGSS inherently has these five attributes. The following discussion is about the effectiveness of using an OOA to deal with the five attributes of an OGSS.

(1) "Frequently, complexity takes the form of a hierarchy, whereby a complex system is decomposed of interrelated subsystems that have in turn their own subsystems until some lowest level elementary components are reached."

Based on the above discussions, an OGSS obviously has this attribute which could be easily represented by using an OOA. This can be shown by a simple example in Figure 3.1. Figure 3.1 presents the subsystems of OGSS. The object-oriented hierarchical structure depicts the whole/partial relationships in an OGSS, which enables to understand, describe, and analyse the system and its parts better (Booch, 1994).

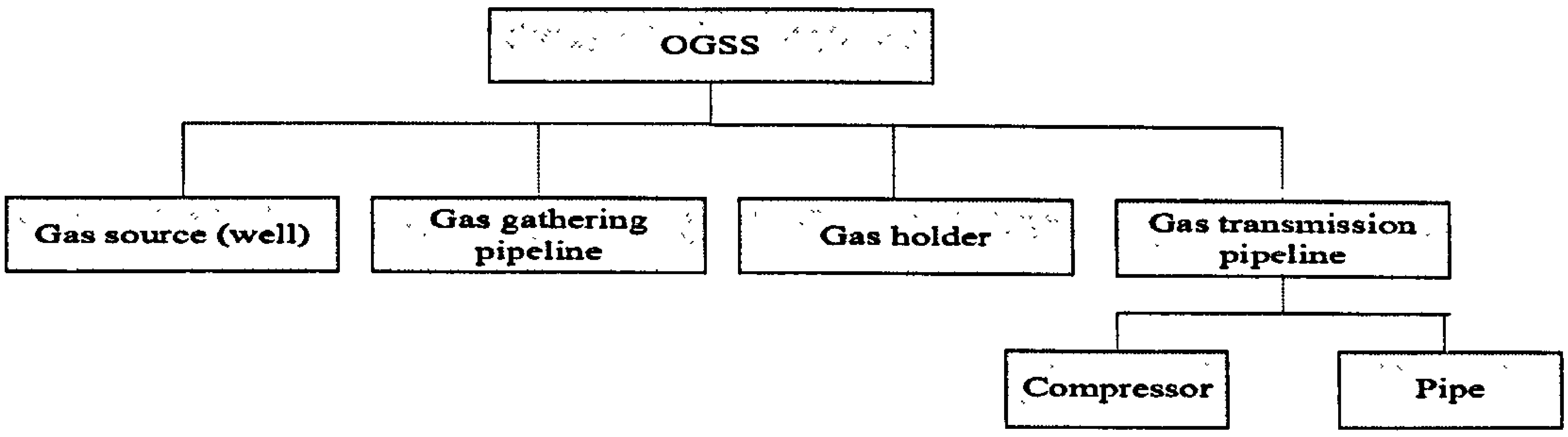


Figure 3.1 Hierarchical structure of an OGSS

Furthermore this hierarchical structure also provides a possible framework for risk assessment. It is obvious within the hierarchy that risk levels of an OGSS are determined by the risk levels of its subsystems (i.e., well, treatment unit, pipe) as well as the hierarchical relationships among them. The risk levels of a subsystem are further determined by the risk levels of its own components. Once the risk levels of each individual component have been determined, aggregation can then be conducted along the hierarchy to generate risks of the subsystems and the overall system.

(2) "The choice of what components in a system are primitive is relatively arbitrary and is largely up to the discretion of the observer of the system."

Primitive elements in this study are deemed as the components that are indecomposable and at the lowest level of a hierarchical structure. They play important roles in risk assessment. However, the determination of primitive elements is arbitrary and depends a lot on the observers of the system because they have different choices of what components are primitive in practical risk assessment. As an example shown in Figure 3.1, a project manager is usually interested in the risks of the overall system (i.e., the risks associated the object at the top of the hierarchical structure) while a gas treatment manager is only interested in the risks within the gas treatment plant which is represented as an object at the second level of hierarchy. Pipe engineers are always interested in the risks associated with different pipes at the bottom level of the hierarchical structure. Due to the different interests of stakeholders, difficulties are consequently introduced in risk assessment of an OGSS. No matter which components are primitive, they are directly related to specific objects in the object-oriented hierarchical structure. This structure can be either truncated at higher levels or extended to lower levels with the changes of primitive elements. This therefore provides a consistent and flexible way of developing hierarchies for different users.

(3) "Intra-component linkages are generally stronger than inter-component linkages. This fact has the effect of separating the high-frequent dynamics of the components, involving the internal structure of the components, from the low-frequent dynamics involving interaction among components."

This difference between intra- and inter-component interactions provides a clear picture of separating various parts of an OGSS, which makes it possible to study risk levels of each part in relative isolation. The object-oriented hierarchical structure in Figure 3.1 is developed with respect to this attribute. For a primitive element in this structure, its risk is usually determined by its own internal states is called state transition diagrams. However, the influences from other elements are relatively smaller and could be neglected in many cases. For a composite object (i.e., treatment plant in this structure) its risk is more directly affected by the constituent components rather than other components (such as well). Actually the object-oriented structure is developed by taking into account intra-component linkages in OGSSs.

(4) "Hierarchical systems are usually composed of only a few different kinds of subsystems in various combinations and arrangements."

This attribute indicates that complex systems have common patterns (Booch, 1994). This is also obvious in the object-oriented structure of OGSSs. A general OGSS is composed of some common elements such as gas sources (wells), risers, gas treatment facilities and gas transmission pipelines. All these elements are further abstracted as fewer common element types or classes like, gas wells, gas treatment plants, pipes, compressors and gas storages (tanks). The overall system is thus a specified arrangement of these different objects or classes. Identification of these basic components is obvious and explicit in an OOA.

(5) "A complex system that works is invariably found to have evolved from a simple system that worked. A complex system designed from scratch never work and cannot be patched up to make it work."

This attribute indicates that an OGSS will work successfully if all its components and subsystems work normally. An OGSS will fail to supply gas to consumers, if some components or subsystems have failed. However direct determination of risk levels of a complex OGSS is difficult or almost impossible. A possible solution to this is indirect evaluation by aggregating the risks of its subsystems (i.e., gas source, gas treatment, etc.) due to their less complexity. These less complex objects are composed of much less complex objects such as wells and pipes, etc. Therefore, risk information can be obtained for a complex OGSS by studying the risks of simpler objects in an object-oriented hierarchical structure. The above discussions not only demonstrate the potential abilities of object-oriented hierarchy in dealing with all the five attributes of complex systems, but also support the development of risk assessment frameworks.

3.3 Object-oriented representation of OGSSs

An object is an abstraction of real world entity described by attributes and methods. Each object can be influenced by the environment or external factors and interact with other objects by receiving and sending messages. Similarly, in risk assessment of an OGSS, the focus is the components in the system. Risks of a gas system are introduced by failures of one or more of the components. External hazards, threats and environmental factors, can only compromise the functions of a gas system by failing its components. With respect to these similarities, it is possible to use object-oriented structures to represent the risk assessment process of OGSSs.

3.3.1 Object-oriented hierarchical structure

The hierarchy of an OGSS is constructed (Figure 3.1) by viewing all the physical elements in an OGSS as objects that encapsulate specific attributes and behaviours and interact with one another. There are two kinds of relationships, aggregation relationship and generalisation relationship which are represented in this hierarchy. These two relationships not only represent an OGSS from a different point of view, but also are useful for risk assessment.

(1) Aggregation relationship

Aggregation represents the "composed of" or "whole/part" relationship, e.g., a gas distribution network is composed of pipes, pumps and tanks, etc. In an OOA, the structure of aggregation is also called object/component structure (Booch, 1994) because it represents the relationships among objects/components. This aggregation relationship also provides a framework for aggregative risk assessment. This indicates that the risk of an OGSS at the top level is determined by the risks of the objects at its lower levels. This research views the real physical elements in an OGSS as primitive objects and puts them at the lowest levels in the hierarchical structure. For each of these primitive objects, states transition diagrams are used to represent its responses to hazards or threats, which are discussed in Section 3.3.2.

(2) Generalisation relation

Generalisation represents the "is kind of" relationship, For example, gathering pipes are a group of smaller interconnected pipelines forming complex networks with the main purpose of bringing natural gas from several nearby wells to a treatment plant or processing facilities. Transmission pipes are used for moving gas from offshore platforms to onshore, between cities, countries and even continents. These transportation networks include several compressor stations in gas lines. All pipe objects (gathering pipes, transmission pipes and risers) belong to a pipe class. Similarly, all offshore wells belong to a gas source class and all compressors belong to a compressor class in an OGSS. With the help of this generalisation process, all the elements of a system are grouped with respect to their "likeliness of behaviour" into classes; these classes are grouped into larger classes and so on (Solomatine, 1996). Finally another hierarchical structure is formed to express the class structure in gas systems.

In the class hierarchical structure, the number of classes is much smaller than the number of objects in the object oriented structure, which thus simplifies the work of assessing risks for primitive objects. For risk assessment, risk analysts need to develop different models for every object in an OGSS. Generic risk analysis models can be developed only for the types of objects or classes and can be used in the object instances.

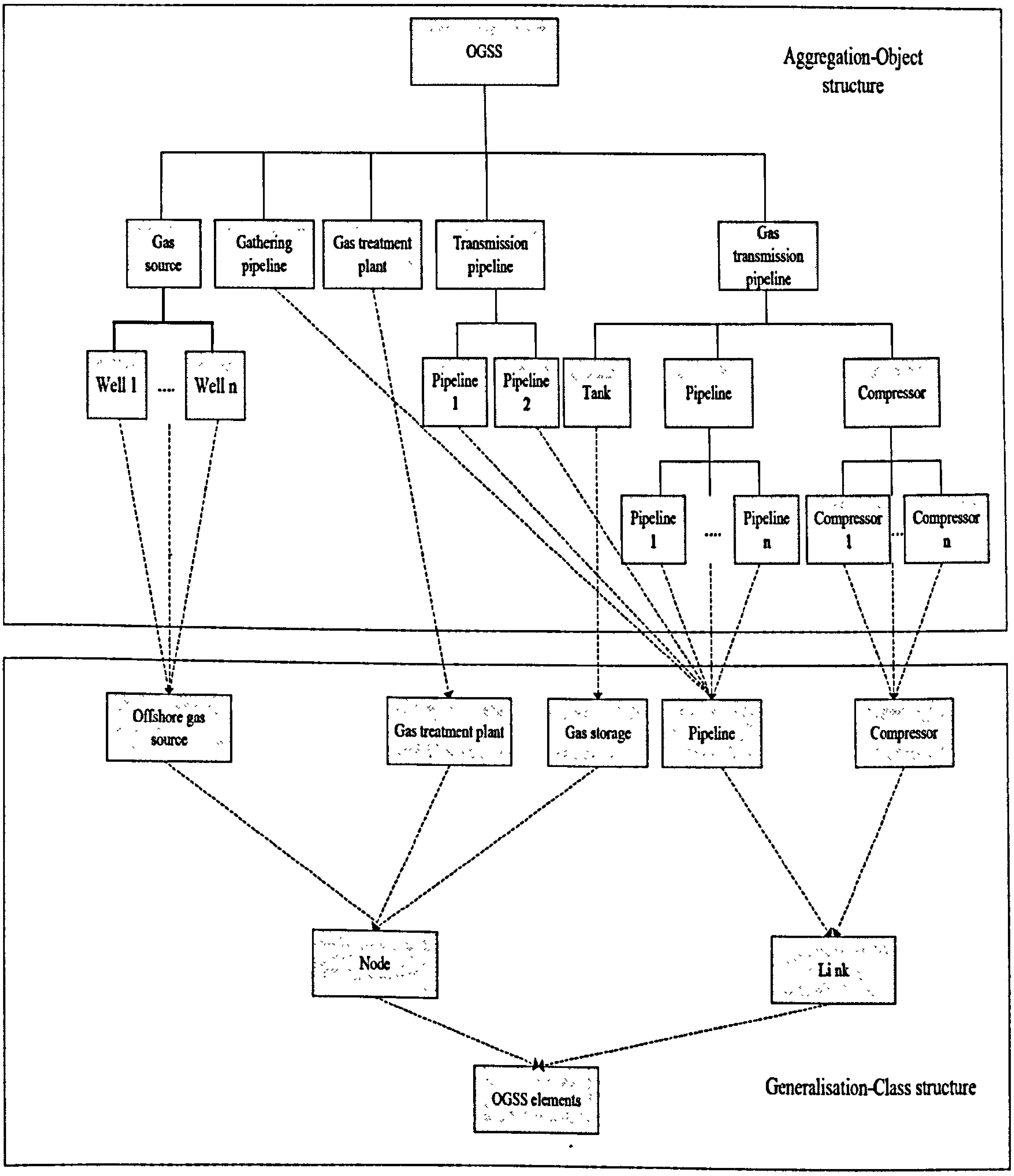


Figure 3.2 Object and class structures of an OGSS

By combining the concepts of the aggregation and generalisation, this study develops frameworks of risk assessment at both the component and system levels in Figure 3.2. Firstly, basic classes are identified on the basis of the class structure of an OGSS. State transition diagrams are used for representing the relationship between hazards, failure states and potential outcome (consequence) for each class. Frameworks of risk assessment (i.e., aggregative risk and fault trees) can be developed at the component level by extracting risk information from the state transition diagrams. Secondly, aggregation relationship provides a framework of aggregative risk assessment at the system level. Interconnections between objects provide a framework of describing the cause-effect relationships at the system level. A more comprehensive view of risks can be obtained by considering the frameworks at both the component and system levels. Furthermore, this is a general method and can be applied to various OGSSs. This method is demonstrated in Figure 3.3.

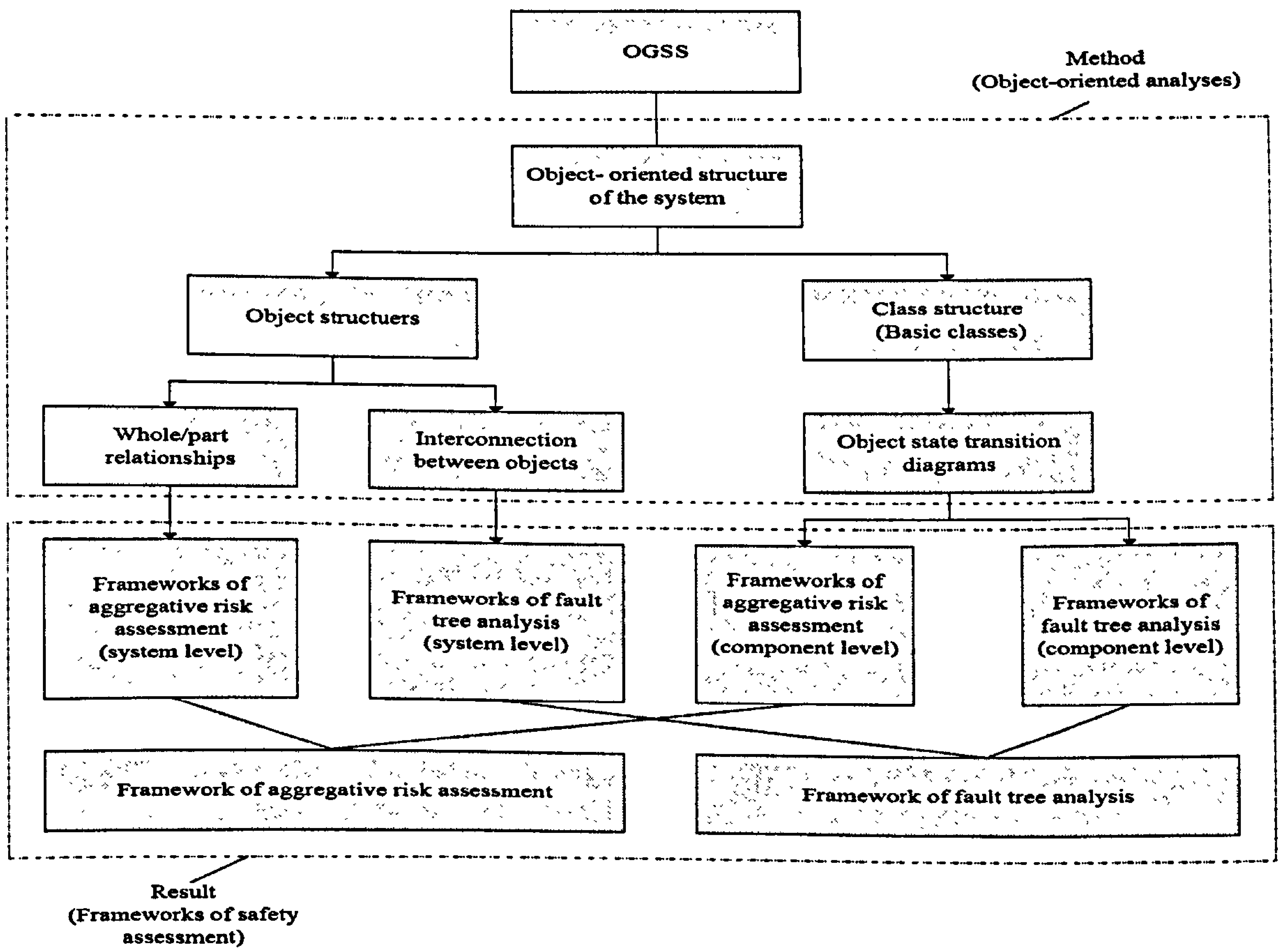


Figure 3.3 Process of developing frameworks of risk assessment for an OGSS based on object-oriented concepts

3.3.2 Object state transition diagram

Figure 3.3 shows that state transition diagrams are an important step to develop a framework of risk assessment at the component level. Therefore, it is necessary to discuss them specifically in this section. In an object-oriented environment, a state transition diagram reveals the state of a given class or object type, the events that cause a transition from one state to another, and the consequences that result from a state change (Booch, 1994). Associated with each object in an OGSS, there are input, output and states (Figure 3.4). Input includes gas flow, external hazards (e.g., flood, etc.) and internal failures (e.g., deterioration, etc.), output denotes the outflow of gas, and states represent the possible states of the component such as working (normal, failure and etc).

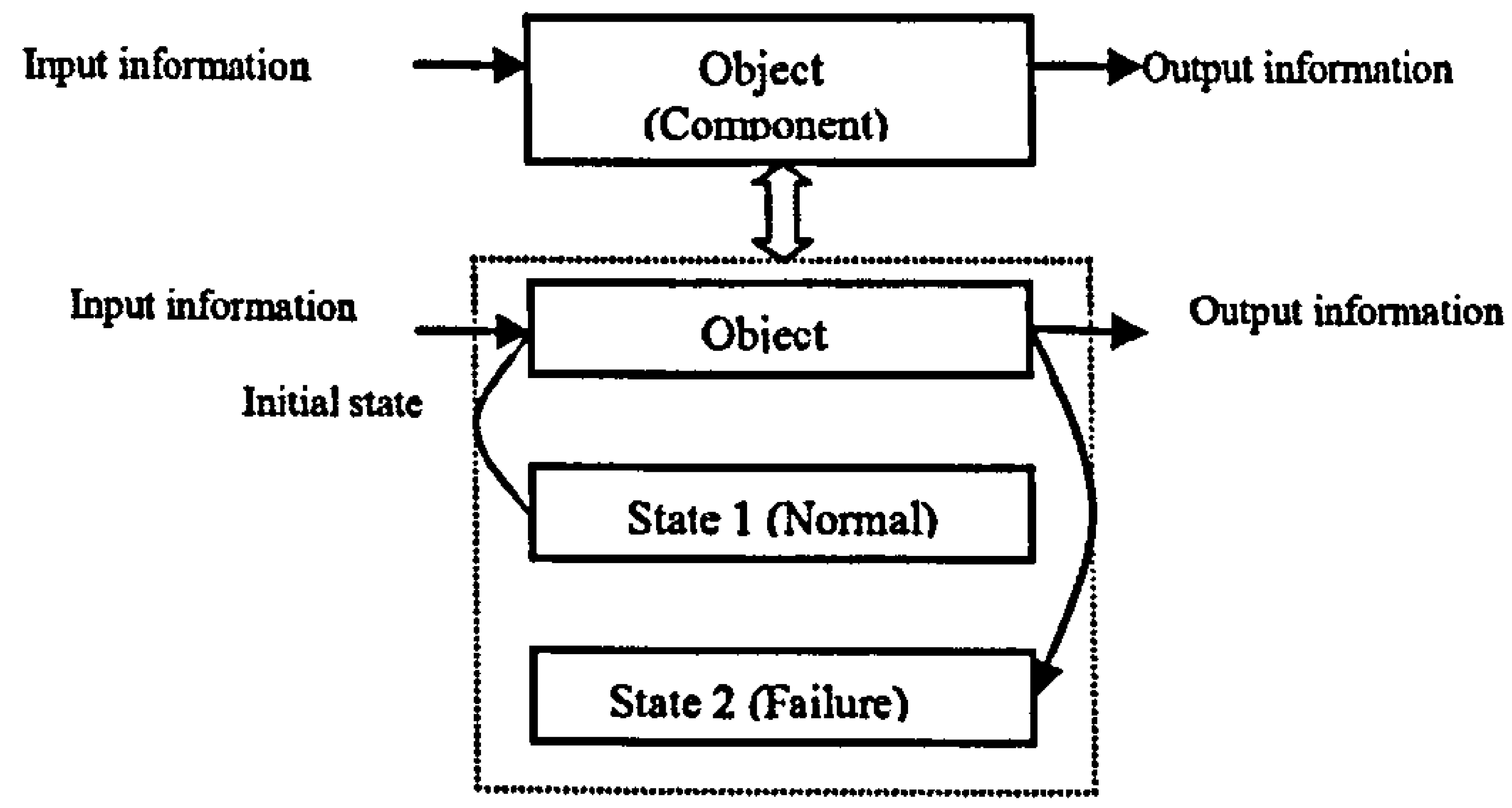


Figure 3.4 State transition diagram of an object due to hazards or threats

An explicit explanation of states transition is illustrated by a pipe example (Figure 3.5). In this example, inputs are external load and gas with flow rate (Qin) and pressure (Hin); outputs are gas with flow rate (Qout) and pressure (Hout); the possible states are normal and leakage; and the methods or behaviours are to transport gas (Figure 3.5). There are three operational scenarios associated with the pipe that are normally considered in practice. In the first scenario, the pipe works normally (Figure 3.5a) and delivers normal gas flow to other components. In the second scenario, the pipe changes its state from normal to leakage due to some internal factors such as deterioration with time (Figure 3.5b). Gas quantity and pressure of outflow is consequently reduced. In the last scenario, the pipe changes its state from normal to leakage due to the overloading from external factors (e.g., objects drop from ships, etc.). Excessive loading force tends to cause longitudinal cracks and results in dramatic reduction of gas quantity. Usually the first scenario represents the normal operation of pipes, while the last two scenarios are specifically applied to a risk or reliability study of gas pipe systems due to the influences of external or internal threats/hazards. It is obvious that hazards, failure states, and possible consequence (outcome) are important factors to develop the state transition diagrams of a specific primitive object.

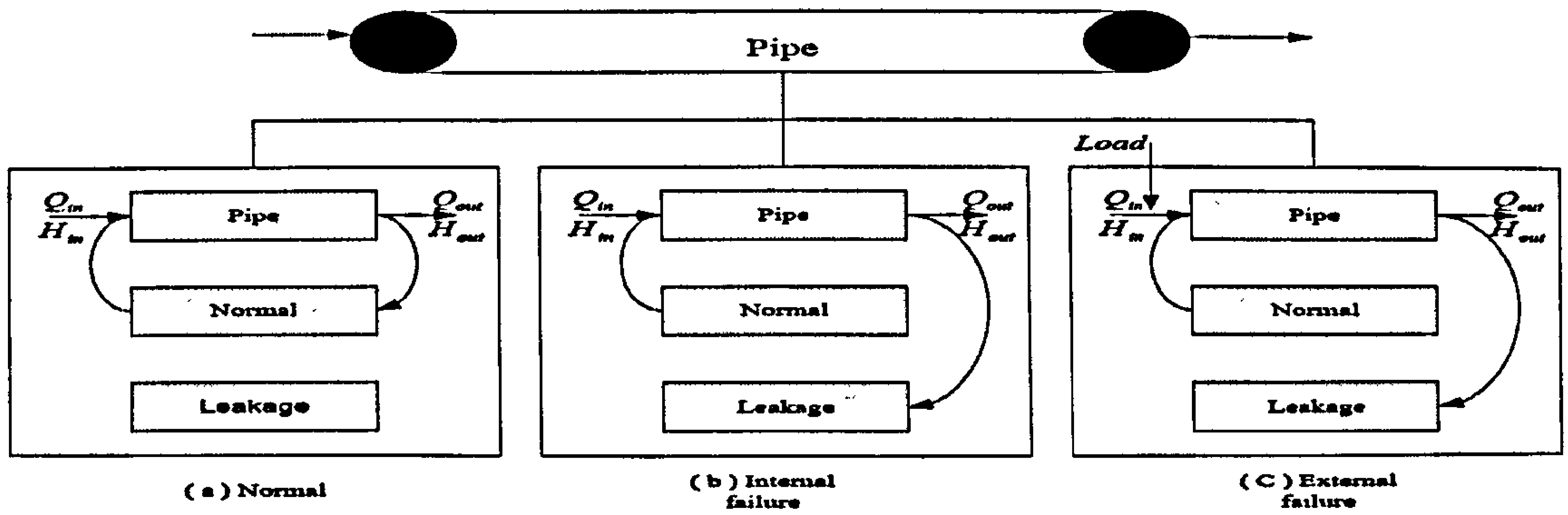


Figure 3.5 Examples of using state transition diagrams to represent operational scenarios of the pipes in an OGSS

According to the object-oriented hierarchical structures (Figure 3.2), five classes are identified in this study as primitive, which include gas source, gas treatment plant, pipe, compressor, and storage. Although an OGSS is also an object, it is usually viewed as a composite object because it usually includes multiple basic objects or components. Risk assessment of these objects is not easily accomplished by directly using state transition diagrams, but can be obtained by using an aggregative method on primitive objects. Associated with each primitive object defined, the relevant hazards, its failure states and related risks are discussed in the following context.

3.3.2.1 Hazards, failure states, and consequence of each primitive object

Possible consequences in an OGSS include reduced gas quantity, reduced pressure and gas leakage. Normally gas quantity and pressure are interactive and the reduction of one factor will lead to the reduction of the other. Considering this and in order to simplify the risk analysis, this study only considers risks of reduced gas quantity and gas leakage specifically.

(1) Gas source (well)

The creation and life of a well can be divided up into five segments: 1. planning, 2. drilling, 3. completion, 4. production and 5. abandoment. Well is created by drilling a hole with diameter from 30 to 36 inches (Mather, 1995) into the earth or sea bed. After the hole is drilled, a steel pipe (casing) slightly smaller than the hole which is secured by the cement will be placed in the hole. The casing provides structural integrity to the newly drilled wellbore in addition to isolating potentially dangerous high pressure zones from each other and from the surface. There are different types of well casing such as conductor casing, intermidate casing and production casing. The primary purpose of conductor casing is to protect the enviroment near the surface of wellbore from being contaminated by leaking gas from deeper underground. Conductor casing is also used to help in the process of circulating the drilling fluid from the bottom of the well to the wellbore. Intermidate casing is the largest section of casing in a well. The primary purpose of intermidate casing is to minimize the hazards coming along with subsurface formation that may affect the well. Production casing provides a conduit from surface of the well to gaseous hyrdocarbons. The size of production casing depends on a number of considerations, including the lifting equipment to be used and the possibility of further drilling in future. For example, if it is considered that the well will be drilled in future time, then the production casing must be wide enough to allow the passage of drill bit in future. Figure 3.6 represents a gas well.

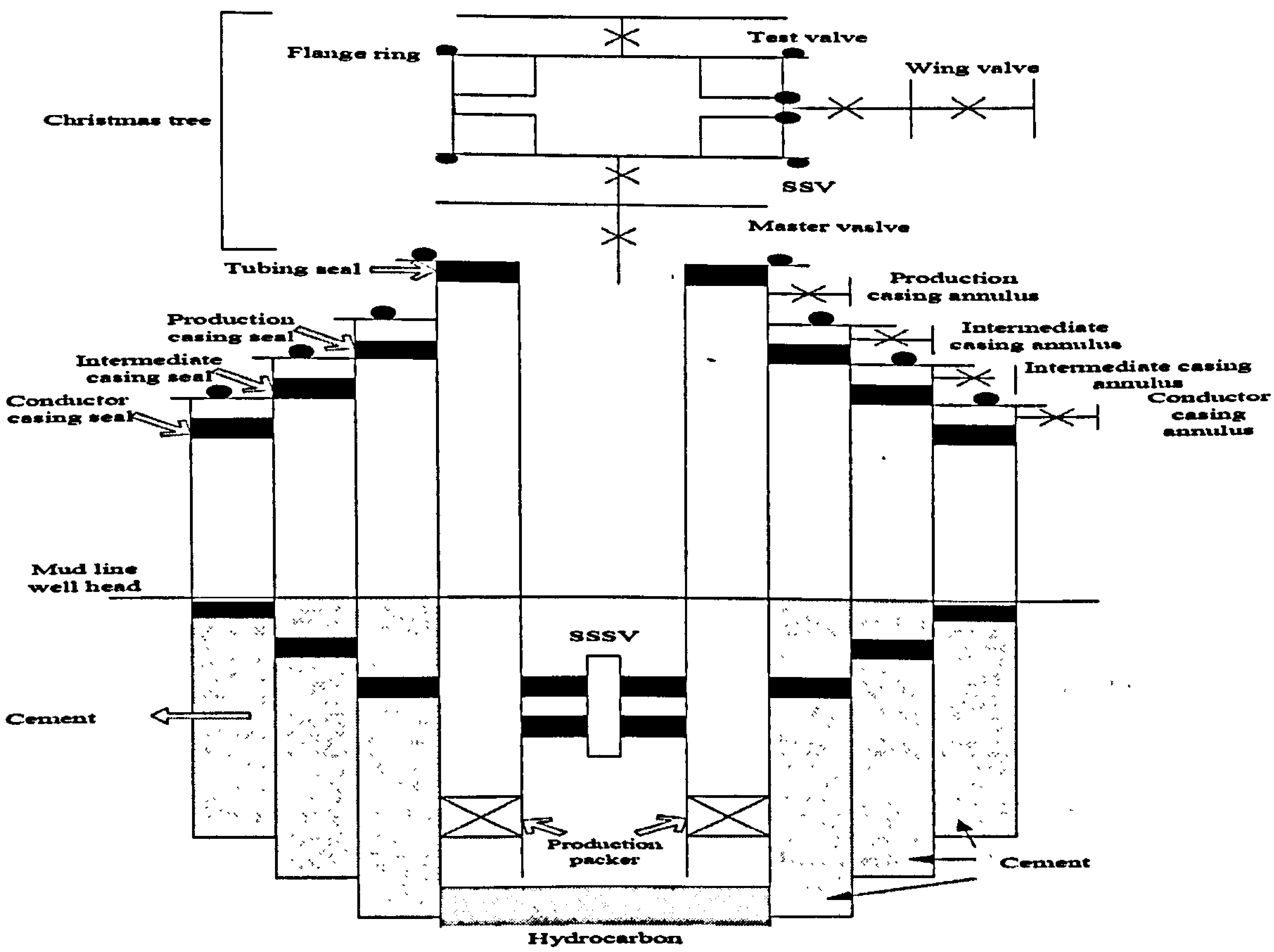


Figure 3.6 An example of gas well

The production stage is the most important stage of a well life, when the gas is produced. Well is usually outfitted with a collection of valves called a Christmas Tree (CT). These valves regulate pressures, control flows and allow access to the wellbore in case that further completion work needs to be performed. From the outlet valve of a CT, the flow can be connected to a transmission pipeline and gas storages (tanks) to supply the product to refineries, natural gas compressor stations and gas distribution networks. The CT is essentially the heart and soul of the offshore (and onshore) hydrocarbon production system. It sits on the top of the wellhead casing system and represents the interface between the well and the production and process facilities. Typical components of a CT are Surface Safety Valve (SSV), Sub Surface Safety Valve (SSSV), Production Master Valve (PMV), Production Wing Valve (PWV), Tree Cap (TC), Pressure Transient Test (PTT), Annulus Vent Valve (AVV), Annulus Master Valve (AMV), Annulus Wing Valve (AWV) and flange.

SSV is a hydraulically actuated fail-safe gate valve for testing gas well with high flow rate, high pressure or the presence of hydrogen sulphide in the system. SSSV is a safety device installed in upper wellbore to provide the emergency closure of the production conduit in the event of an emergency. A PMV is valve located on a CT that controls all flow from the wellbore. The modern CTs are equipped with two master valves referred to as upper and lower master valves. In most cases the lower master valve is manually operated and the upper master valve is operated via a hydraulic or pneumatic actuator and it is connected to the emergency shut down system. PMV is also called the main production barrier valve. Wing valves are incorporated into the "wings" of a CT to provide access to the production tubing for producing and well control purposes. Most CTs have two wings: a production wing connected to the surface production facilities, and a kill wing that may be used for well control or treatment purposes. PWV is also called the secondary production barrier valve. TC is used for covering the top of CT, to prevent ingress of contaminant such as sea water. Annulus is a space surrounding one cylindrical object placed inside another, such as the space surrounding a tubular object placed in a wellbore. AVV is located in the annulus outlet of CT for venting overpressure from the well annulus. AMV is located in the annulus outlet of the CT being the main annulus barrier. AWV is placed in the annulus outlet of the CT being the secondary annulus barrier. Hazards, related failure states and consequences associated with wells in an OGSS are represented in Table 3.1.

Table 3.1 Summary of the basic events, relative failure states and associated consequences with failure of wells in an OGSS

Basic component	Failure state (F)	Hazards/threats (H)	Consequence
Gas source (well)	1. Operational failure		1. Gas leakage
	1.1 Well structural failure		
	1.1.1 Conductor casing failure	1.1.1.1 Cementing job 1.1.1.2 Age 1.1.1.3 Water infiltration	
	1.1.2 Production casing failure	1.1.2.1 Heating of well 1.1.2.2 Type of well completion 1.1.2.3 Galvanic corrosion 1.1.2.4 Tension stress	
	1.1.3 Cement	1.1.3.1 Carbonation of cement 1.1.3.2 Age of cement	
	1.2 Well chemical interaction	1.2.1 Marine fouling 1.2.2 Bio corrosion 1.2.3 Cement carbonation	
	1.3 Well physical interaction	1.3.1 Abrasion of well 1.3.2 Hydrate formation	
	1.4 CT failure	1.4.1 SSSV fail to isolate 1.4.2 PMV fail to isolate 1.4.3 TCP failure 1.4.4 PWV leakage 1.4.5 PT leakage	
	1.5 Annulus failure	1.5.1 Flange failure 1.5.2 AVV failure 1.5.3 AMW failure 1.5.4 AWV failure	
	2. Natural hazards	2.1 Ground movement 2.2 Iceberg collision 2.3 High temperature	1. Gas leakage
	3. Human threats 3.1 Third-party activity	3.1.1 Collision with ship 3.1.2 Fishing trawlers	1. Gas leakage
	3.2 Human threats from terrorist actvity	3.2.1 Terrorist activity	

(2) Pipeline

Pipelines are one of the most important primitives in an OGSS. Extensive research has been performed to analyse the consequences associated with them such as leakage and deterioration, etc. Leakages of pipes can occur due to multiple reasons such as corrosion of the internal or external surfaces of network components; specific events and situations such as ground movement, stresses from excessive gas pressure; and faulty workmanship or construction. Leakage rates can range from a slow leak or "drip" to a large leak which is called a "main break". Examples of typical drips include loose joints, gaskets, or service connections. Typical examples of a break include longitudinal and circumferential cracks in a pipe body. Drips and main breaks usually result in the reduction of gas pressure and consequently gas quantity. Based on the above discussion, hazards, related failure states and consequence associated with pipes in an OGSS can be represented in Table 3.2.

Table 3.2 Summary of the basic events, related failure states and hazards associated with failure of pipes in an OGSS

Basic component	Failure state (F)	Hazards/threats (H)	Consequence
Pipeline	1. Operational failure		1. Gas leakage
	1.1 Defect of pipeline	1.1.1 Bad installation 1.1.2 Bad weld	
	1.2 Design	1.2.1 Unsuitable material 1.2.2 Inadequate strength	
	1.3 Corrosion	1.3.1 Internal corrosion 1.3.2 External corrosion	
	1.3.3 Stress Corrosion Cracking (SCC)	1.3.3.1 Acid 1.3.3.2 High water ratio 1.3.3.3 Tensile stress	
	1.4 Incorrect operation	1.4.1 Inadequate maintenance 1.4.2 Human error	
	2. Natural hazards	2.1 Ground movement 2.2 Current turbidity 2.3 Mud flow	1. Gas leakage
	3. Human threats		1. Gas leakage
	3.1 Third-party	3.1.1 Dropped object 3.1.1Trawling	
	3.2 Human threats from terrorist actvity	3.2.1 Terrorist activity	

(3) Compressor

A gas pump is generally called a compressor, except in very low pressure-rise applications in heating, ventilating and air-conditioning, where the operative equipment consists of fans or blowers. A gas compressor is a mechanical device that increases the pressure of gas by reducing its volume. Compression of gas naturally increases its temperature. Compressors are similar to pumps, both increasing the pressure on a fluid and transporting the fluid through the pipe. As gases are compressible, compressors also reduce the volume of gas. Liquids are incompressible; therefore, the main action of a pump is to transport liquids.

The prime mover is the main power source providing energy to drive the compressor. The prime mover must provide enough power to start the compressor, accelerate it to full speed, and keep the unit operating under various design conditions. This power can be provided by any one of the following sources: electric motors, diesel or natural gas engines, steam engines and turbines. Electric motors are by far the most common type of prime mover. Diesel or natural gas engines are a common compressor power source in the oil and gas industries. Considerations of other factors such as convenience, cost, and the availability of liquid fuel and natural gas play roles in selecting an engine to power a compressor. Figure 3.7 represents a pipeline system.

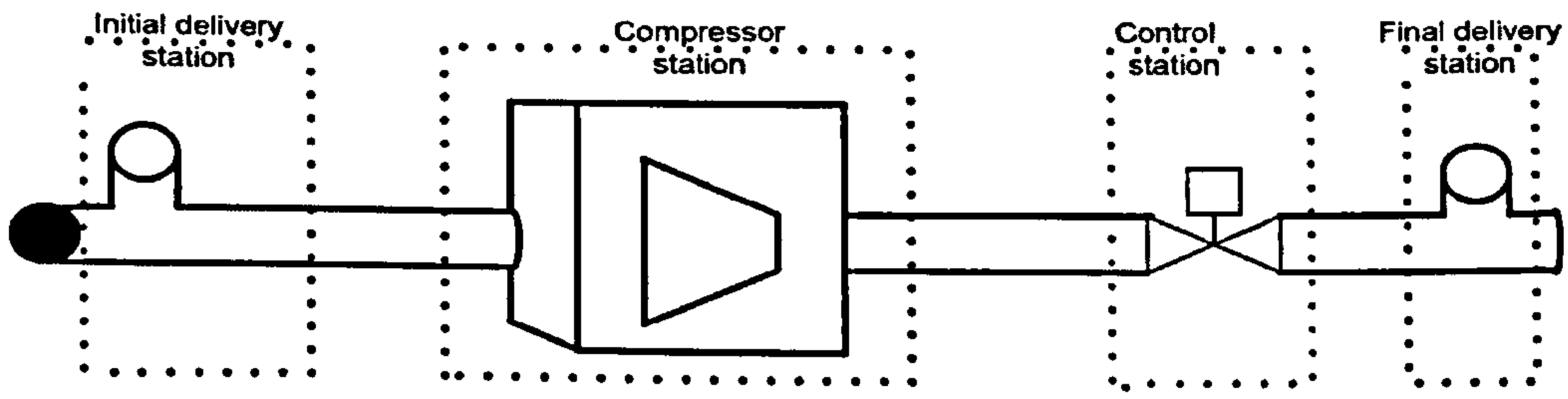


Figure 3.7 Schematic of pipeline and compressor station

Pipeline networks are composed of several pieces of equipment that operate together to move products between different places. The main elements that comprise a pipeline system can be summarized as follows:

1. Initial injection station - known also as supply or inlet station, is basically the beginning of the system. It is the place where the product is injected into the line. Storage facilities, such as tank terminals, as well as other devices to push the product through the line, like pumps or compressor are usually located at these locations.

2. Copmressor station - compressors for gas pipelines are located along the line to help move the product through the pipeline. The location of these stations is defined by the topography of the terrain, the type of product being transported, and operational conditions of the network.

3. Block valve stations - these are the first line of protection for pipelines. With these valves the operators can isolate any segment of the line to perform some specific maintenance work or isolate a rupture or leak. Block valve stations are usually located every 20 to 30 miles, depending on the type of the pipeline. Even though it is not a design rule, it is a very usual practice in OGSSs. Overall the location of these stations depends exclusively on the nature of the product being transported, the trajectory and operational conditions of the pipeline.

4. Regulator station - it is a special type of valve station, where the operators can release some of the pressure built into the lines. Regulators are usually located at the downhill side of a peak.

5. Final delivery station - known also as outlet stations or terminals, through which the product will be distributed to the final consumers. It could be a tank terminal for liquid pipelines or a connection to a distribution network for gas pipelines.

Table 3.3 Summary of the hazards, related failure states and consequence associated with compressors in an OGSS

Basic component	Failure state (F)	Hazards/threats (H)	Consequence
Compressor	1. Operational failure 1.1 Motor failure 1.1.1Mechanical failure 1.1.2 Electrical failure 1.2 Casing failure	1.1.1.1 Rotor /stator failure 1.1.1.2 Brush failure 1.1.1.3 Engine failure 1.1.2.1 Liner supply failure 1.1.2.2 Switch failure 1.1.2.3 Fuse unit failure 1.2.1 Impeller failure 1.2.2 Impeller shaft failure 1.2.3 Shaft bearing failure	1. Reduced gas quantity
	1. Operational failure 1.2 casing failure	1.2.1 Shaft seal failure 1.2.2 Impeller seal failure 1.3 Alarm and monitoring failure 1.4 Inadequate backup 1.5 Gas meter and equipment corrosion 1.6 Vibration and failure of small bore fitting	1. Gas leakage
	2. Natural hazards	2.1 Ground movement 2.2 Current turbidity	1. Gas leakage
	3. Human threats	3.1Terrorist activity 3.2 Incorrect operation	1. Gas leakage

(4) Gas holder facilitiy

Gas holders range in size and complexity from a water sealed gas holder with capacity of $25000m^3$ to a water less gas holder with capacity of $150000m^3$ (Bernatik & Libisova, 2004) .Typically, a gas holder must allow:

1. Filling (the fuel tank must be filled in a secure way).

2. Storage of fuel (the system must contain a given quantity of fuel and must avoid leakage and limit evaporative emissions)

3. Gauging (the remaining quantity of fuel in the tank must be measurable).

4. Venting (if over-pressure is not allowed, the fuel vapors must be managed through valves).

Figure 3.8 shows a large gas holder. Preventing over pressurisation in a large gas holder can be expressed as follows. A compressor drives gaseous hydrogen into the gas holder (tank). The pressure of gas can be controlled by Pressure Reducing Regulator (PRR). In case of high pressure during the filling process, which may be the consequence of the failure of PRR, Pressure Switch (PS) provides a closing signal to the Pneumatic Valve (PV) which will stop the compressor. For over pressure because of any other reason, the tank is equipped with Safety Relief Valves (SRVs), one of which is selected by positioning the Three Port Valve (TPV), and Rupture Disk (RD). The necessity for pressure relief is announced by a horn in the control room triggered by Pressure Indicator Alarm (PIA). The associated rules for system operators are: 1. To turn off the compressor, 2. To close the remotely operated valve. Table 3.5 summaries the hazards, relative failure states and possible consequences associated with gas holder in an OGSS.

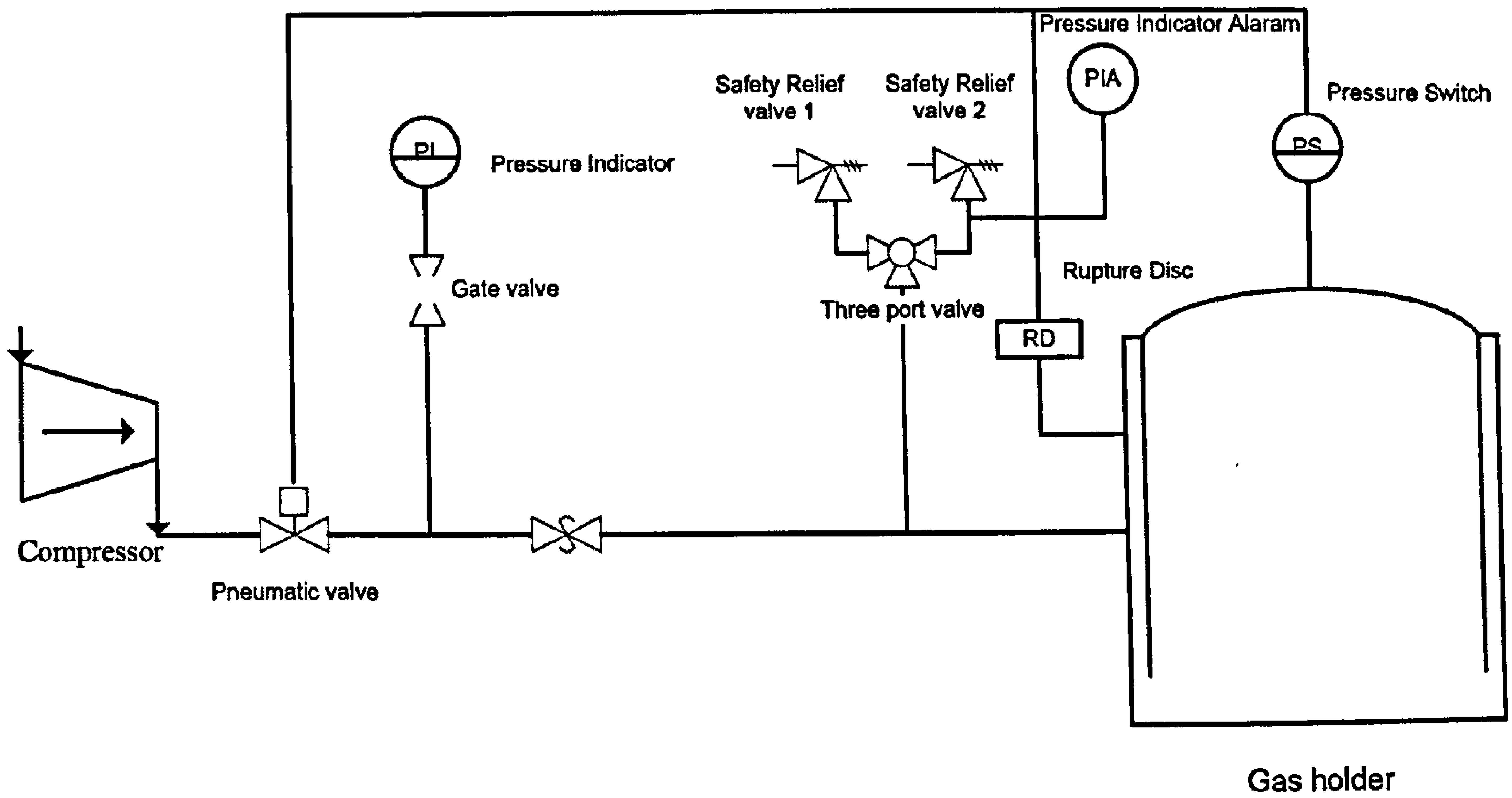


Figure 3.8 Gas holder (tank) diagram

Table 3.4 Summary of the hazards, related failure states and possible consequences associated with gas holders in an OGSS

Basic component	Failure state (F)	Hazards/threats (H)	Consequence
Gas holder	1. Operational failure 1.1 Over pressure 1.1.1 Over filling	 1.1.1.1 PRR failure 1.1.1.2 Automatic interruption not successful 1.1.1.3 Manual filling interruption not successful 1.1.1.4 PV failure 1.1.1.5 PIA failure 1.1.1.6 PS failure	1. Gas leakage
	1.1.2 Pressure relief failure	1.1.2.1 SRVs failure 1.1.2.2 RD failure 1.1.2.3 Fire protection failure 1.1.2.4 TPV failure	
	1.2 Structural failure	1.2.1 Unsuitable material 1.2.2 Inadequate strength 1.2.3 Heavy load	
	1.3 Corrosion 1.3.1 External corrosion	 1.3.1.1 Coating 1.3.1.2 Atmospheric conditions	
	1.3.2 Internal corrosion	1.3.2.1 Gas components 1.3.2.2 Internal coating	
	2. Natural hazards	2.1 Earthquake 2.2 Lightning 2.3 Flood	1. Gas leakage
	3. Human threats	3.1 Terrorist activity 3.2 Inadequate maintenance	1. Gas leakage

3.3.2.2 State transition diagrams of primitive objects in OGSSs

Based on the information identified in Tables 3.1 to 3.4, state transition diagrams are developed to represent the influence of hazards and threats for offshore gas sources, pipes, compressors and gas holders respectively. State transition diagrams for gas compressor are shown in Figure 3.9 and for the rest of components are attached in Appendix 1 (Figures A1.1 to A1.3). State transition diagrams depict the relationships among hazards, failure states, and their related consequences. Hazards are viewed as input information in these diagrams in which an object gives its responses by changing its state from normal to one of the failure states and produces consequence as output information. For example, part of Figure 3.9 shows that the compressor can change its state from normal condition to natural hazard failure state due to ground movement, and consequently produces gas leakage. The hazards (ground movement) and internal state of the object (Natural hazard) drives the states changes and produces possible consequences (Leakage). Furthermore, state transition diagrams are used here to focus on the logic relationships among hazards or threats, failure states, and consequences rather than analysing the likelihood or consequence of a specific hazard or threat. Specific methods of analysing likelihood and consequence of a hazard or threat will be proposed in the ensuing chapters.

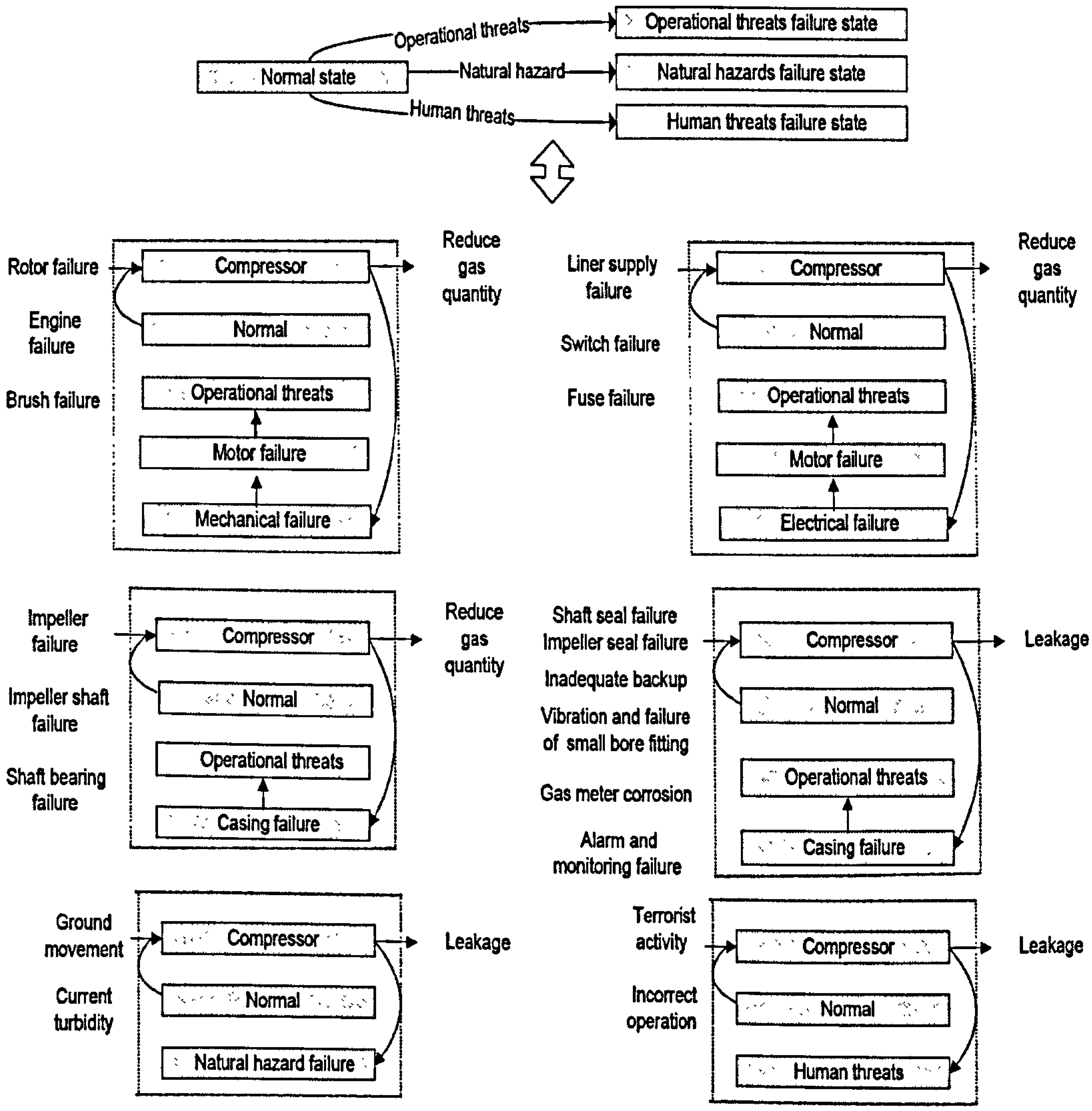


Figure 3.9 State transition diagrams of gas compressors

3.4 Object-oriented frameworks for aggregating risks

3.4.1 Aggregative risk assessment for basic components

(1) General framework of aggregative risk assessment at the component level

A framework of aggregative risk assessment (Figure 3.10) is developed at the component level by extracting the consequence (output) information from object state transition diagrams. In a state transition diagram, failure states are directly related to negative consequences or risks. Thus the risk level of an object is determined directly by the risk levels of its failure states. Further, the change from the normal state to a failure state of an object is directly related to and driven by its specific threats. It is the threat that directly contributes to the risk levels of the failure states. A specific hazard is usually evaluated in terms of its likelihood of occurrence and severity of possible consequence. Then risks can be estimated for such hazards, failure states, and the object respectively by using fuzzy aggregative risk assessment.

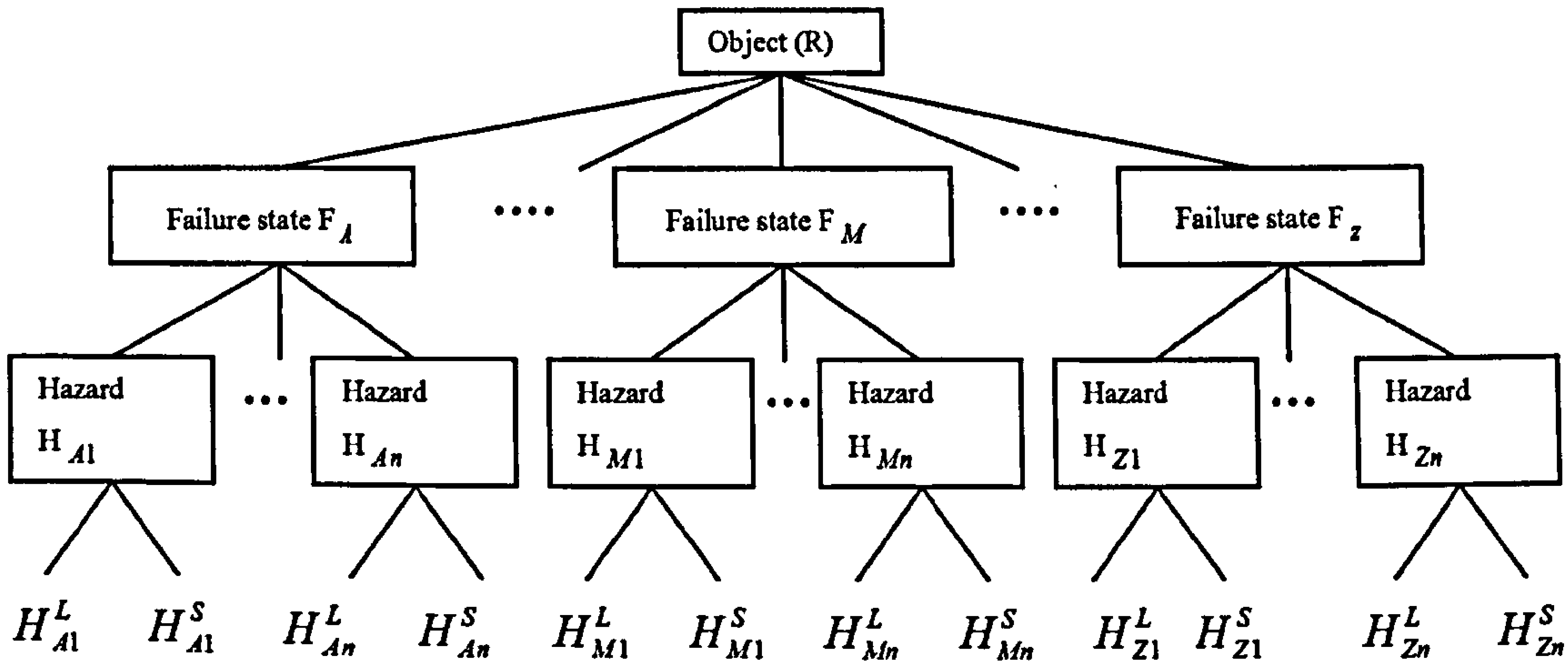


Figure 3.10 Framework of aggregative risk assessment at component levels

According to the above hierarchical structure the conceptual equations for quantitative analysis can be expressed as follows:

$$R = f(F_A, \ldots, F_M, \ldots, F_Z)$$

$$F_M = f(H_{M1}, \ldots, H_{Mn}) \tag{3.1}$$

$$H_{ij} = H^L{}_{ij} \times H^S{}_{ij}\,;\; i = A, \ldots, Z\,;\; j = 1, \ldots, n$$

where R denotes the risk of the object; F_M denotes the risk of failure state M; and H_{ij} denotes the risk of the j th hazard associated with failure state i, which is determined by multiplying the occurrence likelihood, $H_{ij}{}^L$ with severity $H_{ij}{}^S$ of the hazard. The object has failure states of A to M and each failure state has n hazards associated with it.

In order to quantitatively perform Equation (3.1), it is important to consider the following aspects specifically:

Firstly a mathematical function $f(\bullet)$ is required to generate quantitative results for this framework, which will be presented in Chapter 4. Secondly, likelihood and severity are two important factors to evaluate the risk of a hazard or threat.

(2) Frameworks of aggregative risk assessment for primitive objects in an OGSS

With respect to Tables 3.1 to 3.4 and the corresponding state transition diagrams, negative consequences (outcome) are gas leakage and reduced gas quantity in an OGSS. For each primitive object, frameworks are developed to represent risk contributions from hazards to risk of the object (see Figures A1.4 to A1.7 in Appendix 1). As aforementioned, state transition diagrams of objects describe the relation among threats, failure states and object consequences, which thus provide a hierarchical framework for assessment at the component level. In this hierarchical framework, consequences (outcome) are at the top level of the hierarchy and followed by related failure states that are at an intermediate level. Threats (input) are at the bottom level in this framework. As can be seen from the state transition diagram of the compressor (Figure 3.9), leakage and reduced gas quantity are the outcomes (consequence) of the compressor. Construction of risk assessment framework of compressor leakage is presented by Figure 3.11 and described as follows:

1. The outcome of the state transition diagram seats on the top of the hierarchical risk assessment framework.

2. Intermediate levels of the framework are the failure states of well gas leakage (operational threats, natural threats and human threats).

3. Input of each state transition diagram seats on the bottom of the framework and connects with the associated failure states.

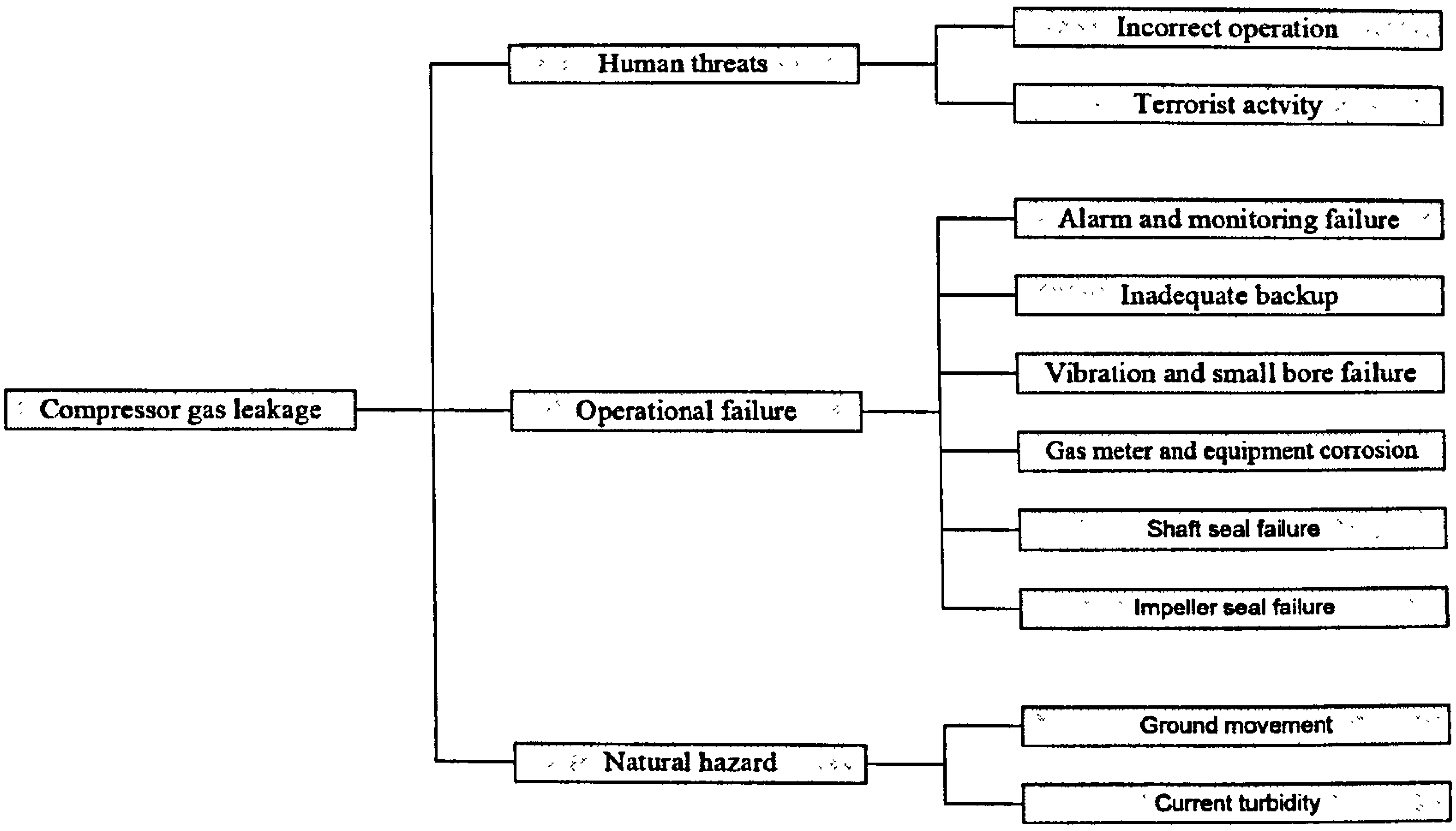


Figure 3.11 Risk of gas leakage

3.4.2 Aggregative risk assessment of subsystems and an overall system

The framework of risk assessment of each subsystem and the overall OGSS is determined by the whole/partial relationships represented in an object-oriented structure (Figure 3.12). In this framework, primitive components are at the bottom level whose risk levels are determined by the framework proposed for aggregative risk assessment (Figure 3.10) in page 64. This aggregative process explicitly shows that the risk of the overall system is determined by the risks of its subsystems, which are in turn determined by the risks of their consistent components.

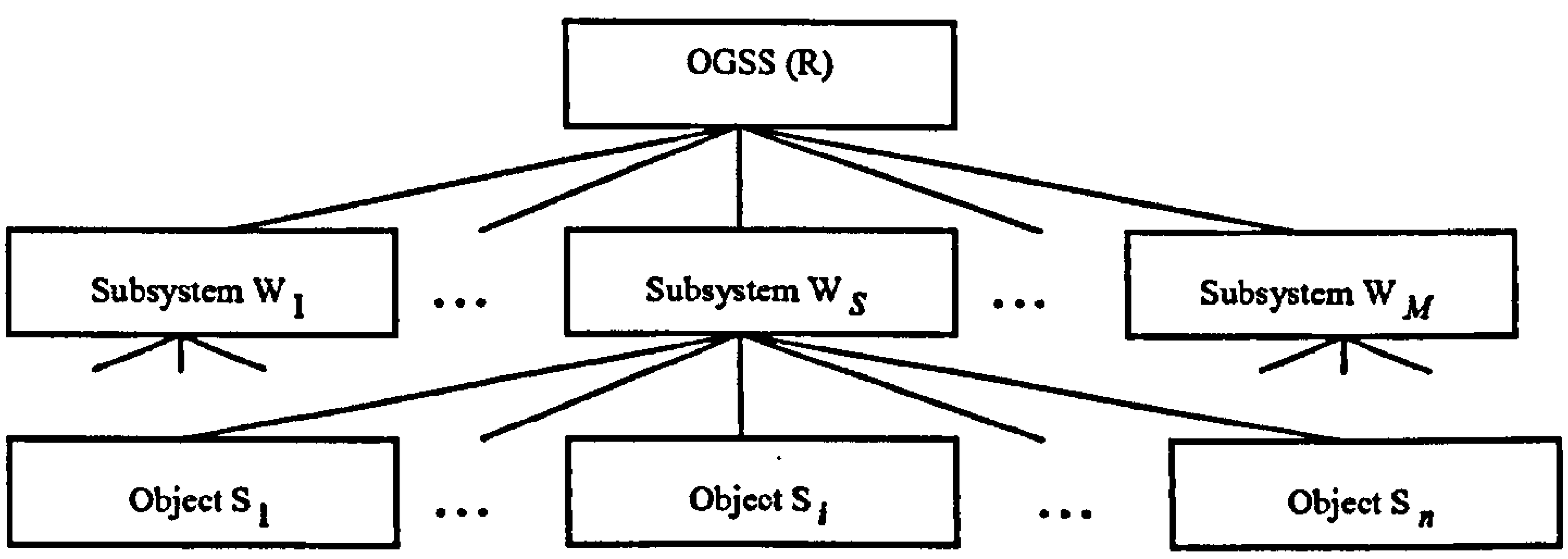


Figure 3.12 Framework of aggregative risk assessment at the system levels

According to this structure, the conceptual equations for quantitative analysis can be expressed as:

$$R = f(W_1, \ldots, W_S, \ldots, W_M)$$

$$W_S = f(S_1, \ldots, S_n) \tag{3.2}$$

where R is the risk of the OGSS; W_s is the risk of subsystem s, and S_i $(i = 1, \ldots, n)$ is the risk of object S_i which is determined by Equation (3.1).

Figure 3.13 gives an example to illustrate the framework of aggregative risk assessment at the system level. In this framework, the risk of the OGSS is determined by its immediate subsystems including well (gas source), gathering pipes, gas treatment plants and gas transmission pipes. For the subsystem gas source, its risk is further determined by the risks of the associated gas wells. A similar process can continue until the risks of all the subsystem are calculated. Finally, by combining the frameworks at the component and system levels, a general framework is formed for aggregative risk assessment of the OGSS. This hierarchical assessment has the ability to model the intricate relationships among the components and subsystems and to account for all the relevant and important elements of risk and uncertainty, therefore rendering the assessment process more tractable and representative. Furthermore, since both of the frameworks are developed from a general point of view, they can be applied to specific applications in various OGSSs. A possible quantitative evaluation of these aggregative frameworks is particularly studied in Chapter 4.

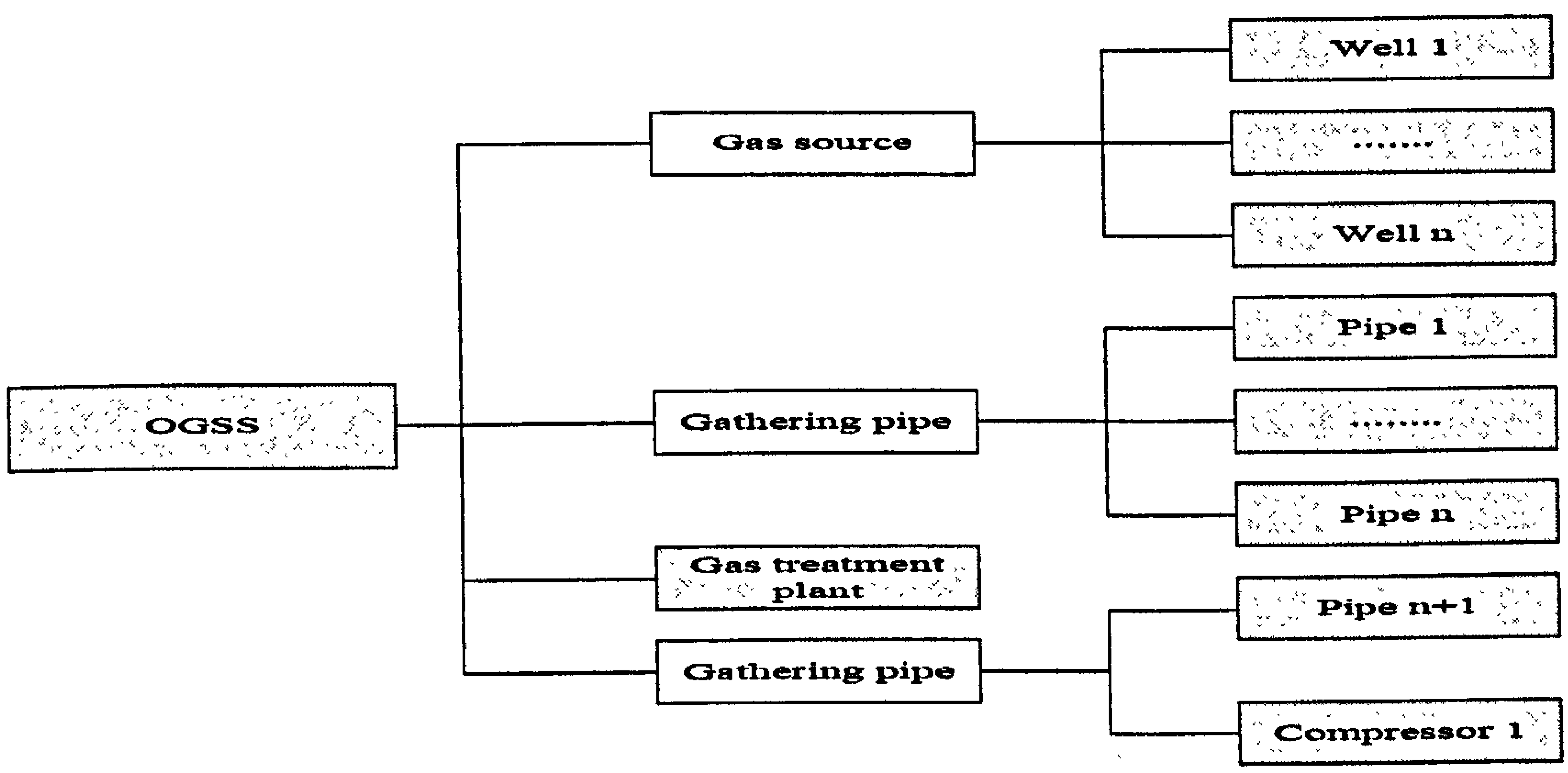


Figure 3.13 Framework of aggregative risk assessment for an OGSS

3.5 Object-oriented FTA

3.5.1 Basics of FTA

The FTA approach was developed by Waston from the Bell Telephone Laboratories in 1961-62 for an Air Force study contract for the Minuteman Launch Control System. The first published paper was presented at the 1965 Safety Symposium sponsored by the University of Washington and the Boeing Company, where a group had been applying and extending the technique. This method has been extensively used in many engineering systems, especially with the development of computer-based analysis techniques since the early 1970s. Nowadays, FTA is viewed as a powerful tool for assessing the failure and reliability of complex large-scale systems.

FTA is a backward analysis tool which begins with a system failure and traces backward, searching for possible causes of the failure. Thus it can identify the causal relationships in an engineering system. In practice, a fault tree is used to provide a logical and hierarchical description of a failure (TE) in terms of sequences and combinations of malfunctions of individual components. Then the reliability or failure of a complex system can be computed in terms of the given probabilities of the component failures. Even though it has been used widely, the construction of fault trees for an engineering system is still as much as an art for a science. To give a consistent risk analysis based on fault trees, the construction process is required to perform at both the component and the system levels. FTA is determined by component interrelationships in a system and its component failure characteristics (Andrew & Moss, 2002). The construction of fault trees is studied, particularly in this section, based on object-oriented concepts. Similar with the development of aggregative risk assessment frameworks described in the previous sections, two steps are proposed here to develop the structure of fault trees, i.e., (1) fault trees at the component level, and (2) fault trees at the system level.

3.5.2 Development of fault trees at a component level

This study applies object state transition diagrams to develop frameworks of fault trees at the component level by extracting the logic relationships between negative consequences, failure states and hazards. With respect to this, three steps are identified in the current study to develop fault tree structures for the objects in an OGSS.

Step 1: Describing the undesired events in terms of different scenarios (i.e., reduced gas quantity and gas leakage).

Step 2: Identifying what failure states can possibly cause the occurrence of an undesired event.

Step 3: Extracting the potential hazards/threats that can possibly alter the object state from normal condition to the failure states identified in Step 2.

These three steps will produce a hierarchical fault tree in which threats (input information of state transition diagram) are at the bottom level and viewed as basic events, and an undesired event of an object is the top event. Figure 3.14 presents these three steps.

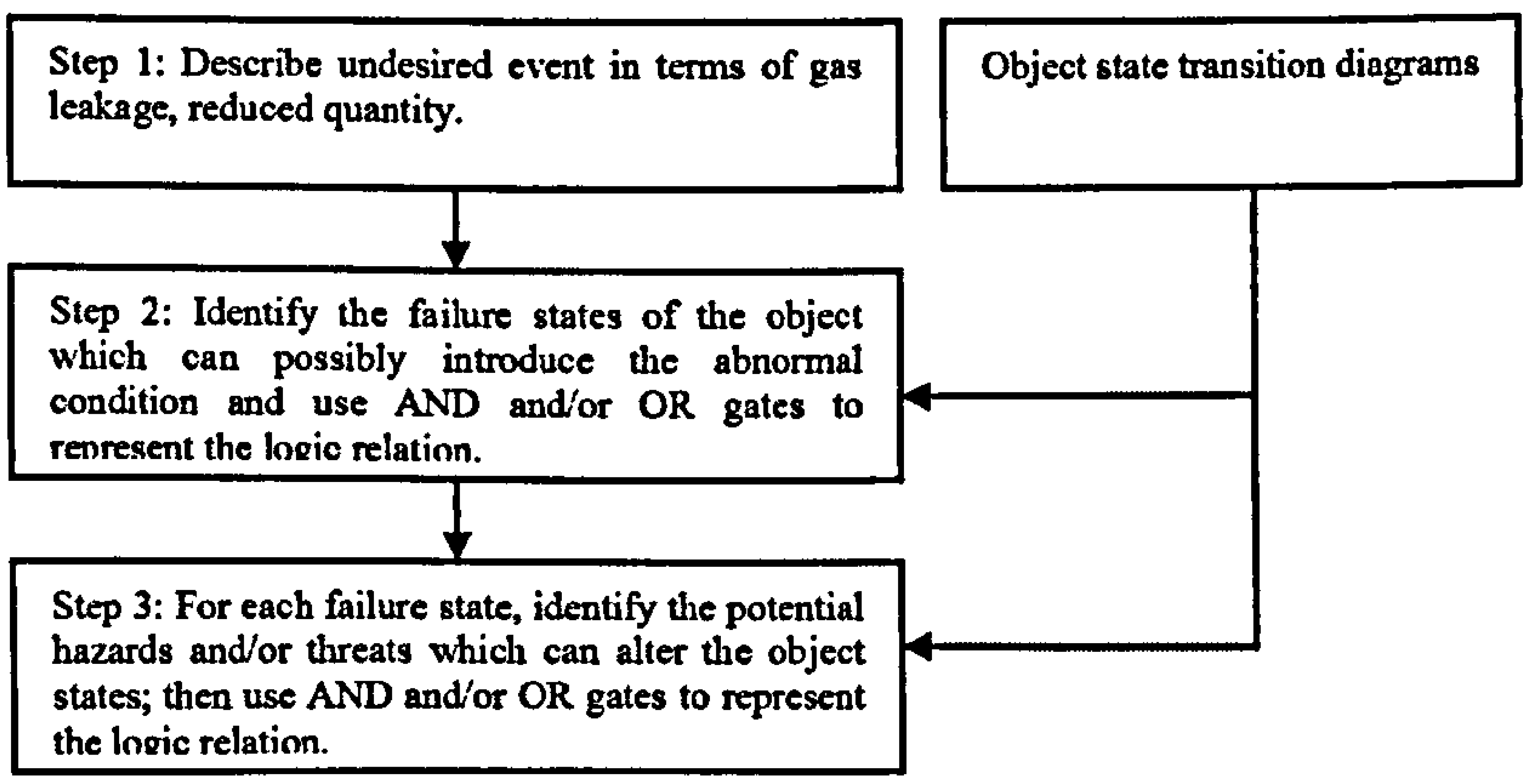


Figure 3.14 Steps of developing fault trees of an object due to its primary hazards by extracting risk information from objects' state transition diagrams

As aforementioned, the three steps provide a cause-effect relationship for a given undesired event of an object. All the primitive objects except the gas compressors have one undesired event: R_1(Gas leakage). The gas compressor has two undesired events R_1(Gas leakage) and R_2 (Gas reduced quantity). F_1, F_2 and F_3 represent the failure states of operational failure, natural hazard failure, and human threat failure respectively. There are other failure states, e.g. operational failure states of gas well including, $F_{1.1}$

(Well structural failure), $F_{1.2}$ (Well chemical interaction), $F_{1.3}$ (Well physical interaction), $F_{1.4}$ (CT failure) and $F_{1.5}$ (Annulus failure) (Table 3.1). All the subsystem hazards and failure states are presented in Tables 3.1 to 3.4. H_{ij} is the hazard j associated with failure state of i, e.g. $H_{1.1.3.1}$ for gas well means the first hazard associated with $F_{1.1.3}$ which is carbonation of cement.

By employing the above three steps, the fault trees for all the subsystems in an OGSS can be constructed. The fault tree of the undesired events for the gas compressor is presented in Figure 3.15 and Figure 3.16. The fault trees of all the other primitive objects are shown in Appendix 1 (Figures A1.8 to Figure A1.10). The undesired events are obtained from the outcomes of state transition diagrams (consequence) and demonstrated as R or R_1 in the fault trees.

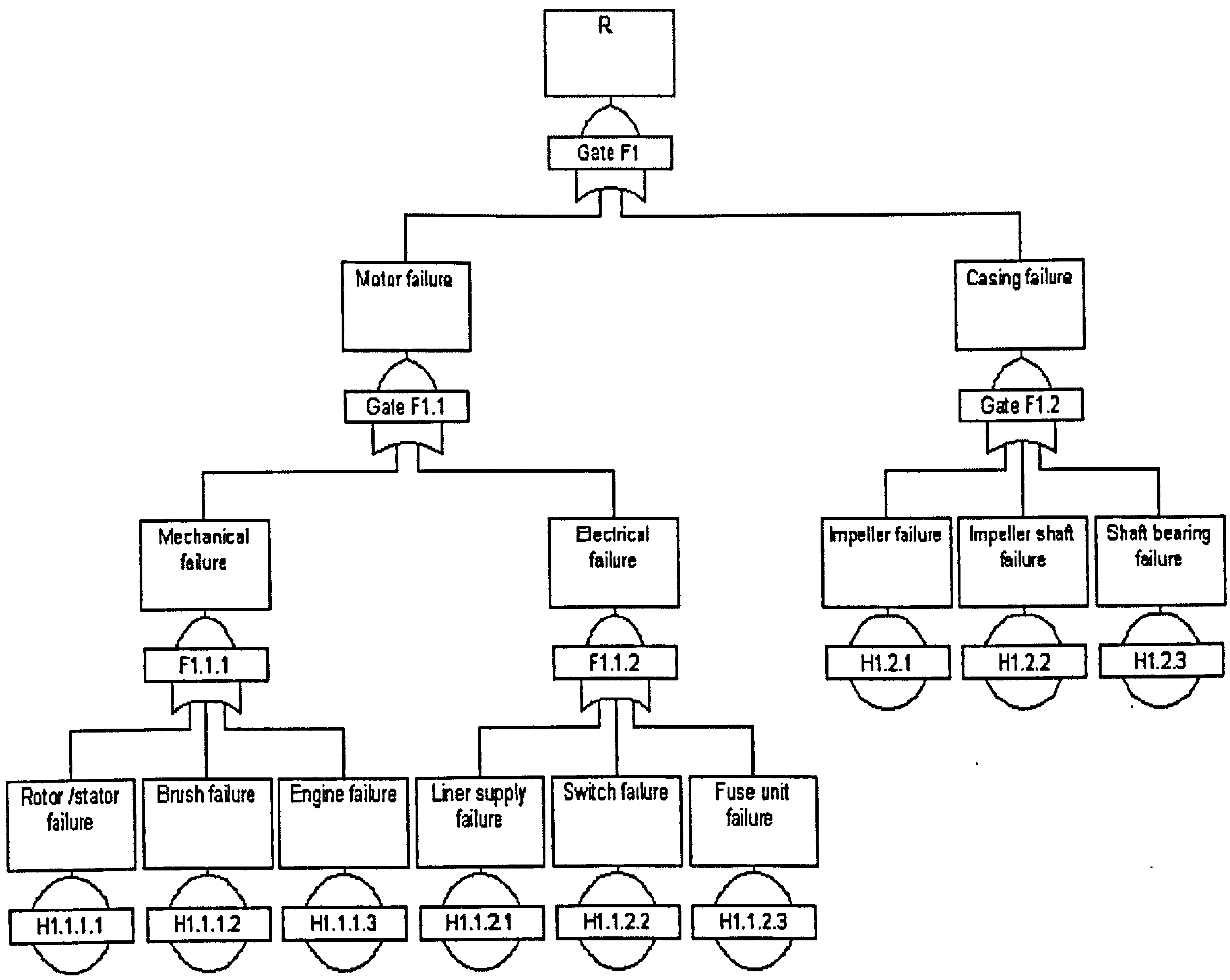


Figure 3.15 Fault tree of reducing gas quantity

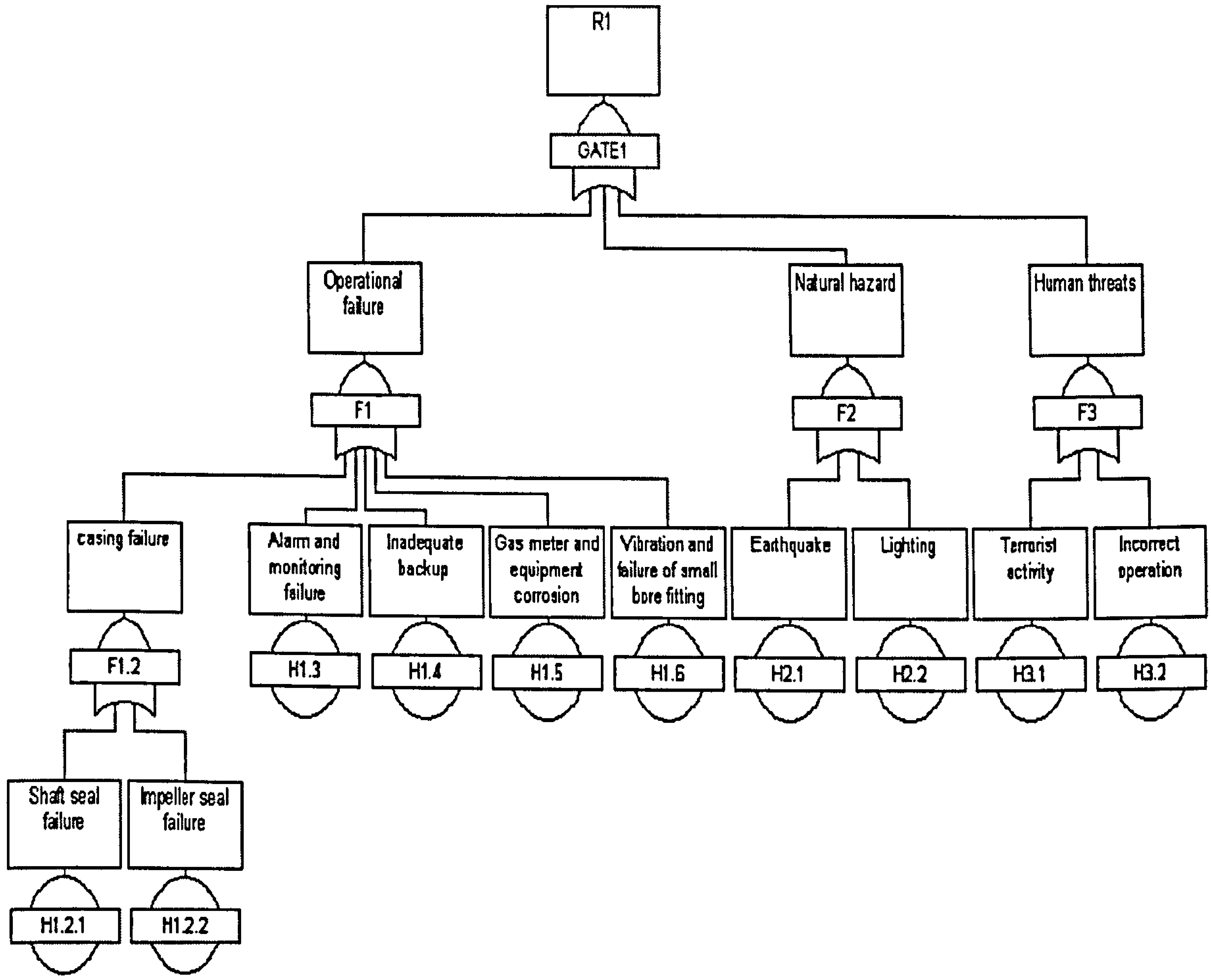


Figure 3.16 Fault tree of compressor gas leakage

3.6 Summary and Comments

This study has shown an OOA is effective in dealing with the complexity in an OGSS, and can be used to develop frameworks of risk assessment for OGSSs. Two types of frameworks are developed in this chapter, aggregative risk assessment and fault trees have been developed on the basis of an object-oriented structure of the OGSS. A framework of aggregative risk assessment is used to evaluate the risks associated with components, subsystems, and the overall system. Fault trees are developed to represent the cause-effect relationships for specific undesired event in a gas system. By combining these two frameworks, risk analysts can obtain a more comprehensive view of the risks in an OGSS. In particular,

- They can be used by different users. The frameworks can be flexibly established at different hierarchical levels according to the requirements of system observers and/or available information.

- They can be reused in different OGSSs. The frameworks are developed from a general point of view, which encapsulates the common features of various OGSSs and can be reused in any specific application.

- They can evaluate risks by considering multiple hazards. The frameworks can aggregate both natural hazards and human-related threats along with a consistent hierarchy to generate useful risk information for decision makers.

- They are flexible to real applications of risk assessment. Even though only reduced gas quantity, gas leakage and gas contamination are considered as risks in this study, the method developed here can be easily reused to other risks (such as low pressure failures, etc.).

However, there are still further works required to improve the frameworks developed in this study, which can be summarised briefly as follows:

- The framework for vulnerability assessment is required to be developed. Vulnerability also plays an important role in introducing risk into an OGSS. However, detailed study is required in order to make the assessment be closer to the real world.

- The process of generating a fault tree structure at the system level is based on the normal flow directions of an OGSS, which is a conservative approximation of the real cases. However, the flow directions might change in real cases of failures. Therefore, further study is necessary to improve the generation of fault trees at the system level so that more reasonable results can be obtained.

Chapter 4

Fuzzy Risk Assessment of OGSSs

Summary

Risk evaluation in OGSSs is a challenging task given that much of the available data is highly uncertain and vague, and many of the mechanisms are complex and difficult to be understood. Consequently, a systematic approach is required to handle both quantitative and qualitative data as well as means to update existing information when new knowledge and data become available. Each basic risk item in a hierarchical framework is expressed by a fuzzy number, which is derived from the composition of the likelihood of a failure event and the associated failure consequence. Analytical hierarchy process is used to estimate weights required for grouping non-commensurate risk sources. The evidential reasoning is employed to incorporate newly arrived data for the updating of existing risk estimates. It is envisaged that the proposed approach could serve as a basis to benchmark acceptable risks in OGSSs.

4.1 Introduction

This chapter presents a method that can quantitatively evaluate the frameworks of aggregative risk assessment of OGSS proposed in Chapter 3. There are two aspects required to be mathematically represented for these frameworks. The first aspect is a mathematical evaluation of risks associated with each basic risk item. A basic risk item in a hierarchical framework is expressed by a trapezoidal fuzzy number, which is derived from the composition of the liklihood of a failure event and the associated severity of its occurrence. The second aspect is a mathematical method that aggregates risk along the hierarchical structure to obtain the risks of objects, subsystems and the overall OGSS. A FAHP methodology is designed to deal with an alternative selection and justification problem by integrating the concept of fuzzy set theory and hierarchical structure analysis. The use of fuzzy methodology allows decision makers to incorporate both qualitative and quantitative data into a decision model. Decision makers usually feel more confident to give interval judgments rather than fixed value judgments

(Chang,1996; Li, 2007). In this approach, fuzzy numbers are used for the preferences of one criterion over another, and then by using the extent analysis method, the synthetic extent value of the pair-wise comparison is calculated. An ER approach is employed to incorporate newly obtained data for the updating of existing risk estimates. Fuzzy aggregative risk assessment which is composed of fuzzy set theory, FAHP and ER theory is adopted to perform quantitative evaluations of aggregative risks in OGSSs.

When a complex system involves various contributory risk items with uncertain sources and magnitudes, it often cannot be treated with mathematical rigor during the initial or screening phase of decision-making (Lee, 1996). It is often difficult to evaluate likelihood and severity associated with a hazardous event using probabilistic theory.

Firstly some hazards may be related to many uncertain factors which are difficult to express in terms of probabilities. For example, human-related attacks or contamination to gas service components are influenced by several uncertain factors like the ability of a human to approach the component, the ability of a human transporting and implanting explosives, the ability of a human obtaining sufficient quantities, and the risk of terrorists attacks. All of such factors are subjective and difficult to represent by a single precise probability distribution function.

Secondly, historical records of some risk scenarios, particularly extreme hazardous events (e.g., extreme current turbidity, terrorist activity, etc.) are often incomplete and insufficient. Thus, an analyst may have the difficulties in developing proper probability distribution functions with limited data.

Due to lack of data, risk analysts may be more confident with linguistic representations (such as very high, slightly low, etc.). However, probabilistic variables have limited ability to represent this linguistic or descriptive information.

Additionally, it may be necessary to carry out risk assessment based on multiple hazards which are represented in various forms, such as probabilistic data, experts opinions and linguistic representations. Traditional probabilistic risk assessment approaches may lack the ability to deal with such multi-form data input. Therefore, there is a need to develop an effective method to address the above characteristics of risk assessment.

As an alternative to probabilistic theory, fuzzy set theory was introduced by Zadeh (1965) to deal with the problems in which vagueness is presented. Fuzzy set theory can be used to represent subjective, vague, linguistic and imprecise data and information effectively. Applications of fuzzy set theory have been extensively studied with respect to the ambiguity and vagueness involved in the risk analysis in different engineering areas. Lee (1996) applied fuzzy set theory to evaluate the rate of aggregative risk in software development. Chen (2001) used fuzzy group decision making for evaluating the rate of aggregative risk in software development. Sadiq & Husain (2005) applied a fuzzy-based methodology for an aggregative environmental risk assessment of drilling waste. Zeng et al. (2006) applied an aggregative risk assessment model for information technology project development. Wang & Elhag (2007) used fuzzy group decision making for bridge risk assessment. The proposed methodology in this chapter is built upon the previous development of FARA. The novel parts of the proposed methodology are to combine both qualitative and quantitative information and to update information based on the new evidence by using Intelligent Decision System (IDS) via an ER approach.

4.2 Fuzzy set theory

Fuzzy set theory, formalised in 1965, has been widely applied in different fields. Its applications in system safety and reliability analysis could prove to be useful since such an analysis often requires the use of subjective judgments and uncertain data. The use of linguistic variables provides flexible modelling of imprecise data and information. The significance of fuzzy variables is to facilitate gradual transition between states. Therefore, they are able to deal with observation and measurement of uncertainties. When dealing with the safety of a system using fuzzy set theory, probabilities can be estimated using linguistic variables. A linguistic variable differs from a numerical variable in that its value is not numbers but words and sentences in natural or artificial language (Pillay & Wang, 2003). The concept of linguistic variables serves the purpose of providing a means of approximate characterisation of phenomena, which is too complex or ill defined to be manageable for description in conventional quantitative terms.

Classical set contains objects that satisfy precise properties of membership. Fuzzy sets, on the other hand, contain objects that satisfy the imprecise properties of membership. For example, membership of an object in a fuzzy set can be partial. For classical sets, element x in a universe U is either a member of a crisp set A or is not. This binary issue of membership can be represented mathematically by:

$$X_A = \begin{cases} 1, x \in A \\ 0, x \notin A \end{cases} \tag{4.1}$$

Zadeh extended the notion of binary membership to accommodate various degrees of membership on the real continuous interval $[0,1]$, where the endpoints of 0 and 1 conform to no membership and full membership respectively (Zadeh, 1965). The sets of universe U that can accommodate degrees of membership were termed by Zadeh as fuzzy sets. Hence, a fuzzy set can be represented by functional mapping as $\mu_{\tilde{A}}(x) \in [0,1]$, where $\mu_{\tilde{A}}(x)$ is degree of membership of element x in fuzzy set $\tilde{A}$ or simply membership function of $\tilde{A}$. The value $\mu_{\tilde{A}}(x)$ is on the unit interval that measures the degree to which element x belongs to $\tilde{A}$. The larger $\mu_{\tilde{A}}(x)$ is the stronger degree of x belongs to $\tilde{A}$. In this study two special kinds of fuzzy numbers including triangular fuzzy numbers and trapezoidal fuzzy numbers are employed. A triangular fuzzy number can be defined by a triplet as follows:

$$\tilde{\mu}_A(x) = \begin{cases} 0, x \leq a_1 \\ \dfrac{x - a_1}{a_2 - a_1}, x \in [a_1, a_2] \\ 1, x = a_2 \\ \dfrac{a_3 - x}{a_3 - a_2}, x \in [a_2, a_3] \\ 0, x \geq a_3 \end{cases} \tag{4.2}$$

where a_2 is called the mean value of $\tilde{A}$, a_2 and a_3 represent the lower bound and upper bound, respectively. Let $\tilde{A} = (a_1, a_2, a_3)$ and $\tilde{B} = (b_1, b_2, b_3)$ be two triangular fuzzy numbers. In this situation, the extended fuzzy operations can be defined as follows:

Change of sign: $-(a_1, a_2, a_3) = (-a_3, -a_2, -a_1)$ (4.3)

$$\text{Addition}\oplus:(a_1,a_2,a_3)\oplus(b_{12},b_2,b_3)=(a_1+b_1,a_2+b_2,a_3+b_3) \quad (4.4)$$

$$\text{Subtraction}-:(a_1,a_2,a_3)-(b_1,b_2,b_3)=(a_1-b_3,a_2-b_2,a_3-b_1) \quad (4.5)$$

$$\text{Multiplication }\otimes:(a_1,a_2,a_3)\otimes(b_1,b_2,b_3)=(a_1b_1,a_2b_2,a_3b_3) \quad (4.6)$$

$$\text{Inverse: }(a_1,a_2,a_3)^{-1'}=(\frac{1}{a_3},\frac{1}{a_2},\frac{1}{a_1}) \quad (4.7)$$

$$\text{Division}\div:(a_1,a_2,a_{_3})\div(b_1,b_2,b_3)=(\frac{a_1}{b_3},\frac{a_2}{b_2},\frac{a_3}{b_1}) \quad (4.8)$$

Let $\widetilde{A}=(a_1,a_2,a_3,a_4)$ denote the trapezoidal fuzzy number, where $[a_1,a_4]$ is the support of $\widetilde{A}$ and $[a_2,a_3]$ is its modal set.

$$\widetilde{\mu}_A(x)=\begin{cases}0, x\le a_1\\ \frac{x-a_1}{a_2-a_1}, x\in[a_1,a_2]\\ 1, x=[a_2,a_3]\\ \frac{a_4-x}{a_4-a_3}, x\in[a_3,a_4]\\ 0, x\ge a_4\end{cases} \quad (4.9)$$

Let $\widetilde{A}=(a_1,a_2,a_3,a_4)$ and $\widetilde{B}=(b_1,b_2,b_3,b_4)$ be two trapezoidal fuzzy numbers. The arithmetic operations on the proposed fuzzy numbers can be defined as follows:

$$\text{Change of sign: }-(a_1,a_2,a_3,a_4)=(-a_4,-a_3,-a_2,-a_1) \quad (4.10)$$

$$\text{Addition}\oplus:(a_1,a_2,a_3,a_4)\oplus(b_1,b_2,b_3,b_4)=(a_1+b_1,a_2+b_2,a_3+b_3,a_4+b_4) \quad (4.11)$$

$$\text{Subtraction}-:(a_1,a_2,a_3,a_4)-(b_1,b_2,b_3,b_4)=(a_1-b_4,a_2-b_3,a_3-b_2,a_4-b_1) \quad (4.12)$$

$$\text{Multiplication}\otimes:(a_1,a_2,a_3,a_4)\otimes(b_1,b_2,b_3,b_4)=(a_1b_1,a_2b_2,a_3b_3,a_4b_4) \quad (4.13)$$

$$\text{Inverse: }(a_1,a_2,a_3,a_4)^{-1'}=(\frac{1}{a_4},\frac{1}{a_3},\frac{1}{a_2},\frac{1}{a_1}) \quad (4.14)$$

$$\text{Division }\div:(a_1,a_2,a_3,a_4)\div(b_1,b_2,b_3,b_4)=(\frac{a_1}{b_4},\frac{a_2}{b_3},\frac{a_3}{b_2},\frac{a_4}{b_1}) \quad (4.15)$$

4.3 Research methodology

In the circumstances where there is a lack of data, it is necessary to incorporate expert judgments into a risk study. A framework is established based on fuzzy set theory, ER and FAHP methods. The proposed framework is capable of quantifying judgments from experts who express their opinions qualitatively. The first step of the proposed framework is to obtain the risk of each hazard by using fuzzy set theory. This step includes five sub-steps which are explained in Section 4.4.2. The second step is to calculate weight factors for each hazard in the framework. Since the study incorporates fuzzy set theory into an AHP method, a set of linguistic priority terms along with the membership functions describing the relationship between elements in each hierarchy of the AHP is adopted. Thus, the pair-wise comparisons between the elements in each hierarchy using fuzzy set theory are established. The fuzzy expressions are subsequently converted into a single crisp value using an appropriate defuzzification method. This is followed by the weighting vector calculation so as to obtain the relative importance of element. By repeating the steps above, the risk of each element in the hierarchy is acquired based on the normalised weight factors calculated. Lastly, in case of obtaining new evidence, the ER method is employed to incorporate new evidence for updating the existing risk estimates in the system. Risk assessment can be carried out for each subsystem and finally for the OGSS. The following three steps are used in the proposed risk analysis:

Step 1: Application of fuzzy risk assessment for risk analysis of a hazardous element.

Step 2: Application of FAHP to synthesise the information produced at different hierarchical levels to obtain the overall risk estimate at the system level.

Step 3: Application of ER to incorporate new data for updating the existing risk estimate.

Figure 4.1 demonstrates the research methodology. Each step of the framework is discussed in the following sections.

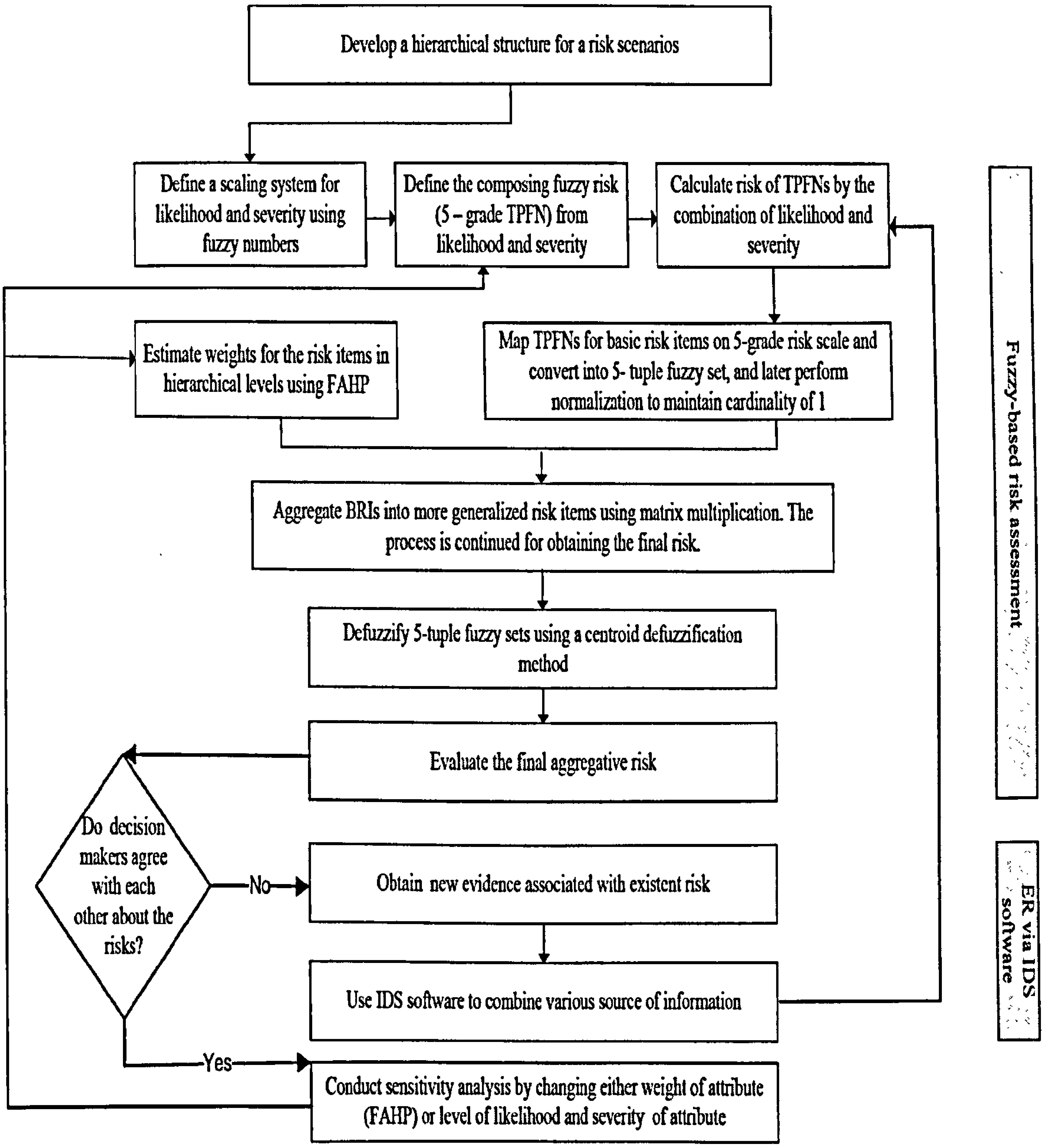


Figure 4.1 The research methodology of risk assessment of OGSSs

4.4 FRA

Risk can be obtained by Equation 4.16 as follows:

$$R = L \otimes S \tag{4.16}$$

where R is the risk associated with each hazardous event, L represents the likelihood of the hazard, S represents the severity or consequence of the hazard and $\otimes$ denotes the multiplication relationship between likelihood and severity. This definition has been applied to risk assessment in many applications such as software development (Lee, 1996), environment modelling (Sadiq et al., 2004), mechanical system design (Wang et al., 1995), process plant modelling (Khan et al., 2002, 2004; Khan & Haddara, 2003; Krishnasamy et al., 2005) and water pipe deterioration analysis (Kleiner et al., 2006 a,b). In this chapter, Equation 4.16 is used to describe the risk levels associated with each hazardous event in the OGSS. This definition indicates that if L and/or S are represented by fuzzy numbers, R will also be a fuzzy number. This calculation can be performed by using fuzzy operation rules.

4.4.1 Linguistic risk levels

In risk assessment, it is not unusual for analysts to prefer describing risks in terms of different levels, such as high, medium, low, rather than absolute values. This descriptive method may be necessary due to several reasons.

Risk is not absolutely objective in nature, but rather relative and subjective. It is usually a fuzzy concept in the sense that there is not any unique risk associated with a hazardous event occurring in a given period (Karwowski & Mital, 1986). Therefore, risk assessment deals with quantities which are inherently imprecise and whose future values are uncertain. Linguistic categories or levels (e.g., very high, high, medium, low, very low), instead of absolute numbers, are adopted because each linguistic category or level can deal with the various and uncertain risk values by including a range or set of numbers.

The real meaning of risk in practice is varied and application-specific. Risks are thus measured in different units. Even similar risk values may indicate different levels of influence in different applications. It is usually difficult to compare or aggregate risks with different units in a risk assessment as an alternative to numerical values for measuring risk levels, expert judgment using linguistic terms can be more easily used by risk analysts, system managers, policy makers and general users.

Additionally, it is not unusual for analysts to have more confidence in risk evaluations performed in terms of risk levels rather than numerical values under certain circumstances. The risk of terrorist attacks on an OGSS can be used as an example. An analyst cannot provide exact estimates for assessing risk in many situations; therefore, it is preferred to assess risk using linguistic terms rather than numerical values. This research uses linguistic risk levels to represent risk items. Furthermore, the numbers associated with linguistic risk levels are also considered as an important factor in practical risk assessment by many researchers.

In 1956, Miller published a paper entitled "*The magical number seven, plus or minus two: Some limits on our capacity for processing information*" (Miller,1956). With respect to this, it is often recommended that the number of linguistic terms for judgments should be restricted between five to nine (Karwowski & Mital, 1986). Normally, too few terms will not be adequate to present the real knowledge of analysts, while too many terms will bring extra difficulties in the following assessment. Therefore, five categories of linguistic representations are adopted in this research to express the degrees of (Likelihood) L and (Severity) S of hazards. It should be noted that there are some hazards with known occurrence L. L can be converted into qualitative grade such as: Very low, Low, Medium, High and Very high as represented in Table 4.1 (Military Standard, 1993; Pillay & Wang, 2003). Each of these linguistic terms can be represented quantitatively by a range of probabilities. Table 4.1 can provide a guideline for analysts carrying out such an analysis and can be used for converting the quantitative occurrence L of hazards into its corresponding linguistic terms.

Table 4.1 Assessment of hazard probabilities and corresponding linguistic terms

Linguistic terms for assessing L of risk (Grade of L)	Qualitative	Quantitative
1. Very low	Unlikely to occur	Occurrence $L < 10^{-6}$
2. Low	Unlikely, but possible to occur in lifetime of an item	$10^{-6} \leq$ Occurrence $L < 10^{-3}$
3. Medium	Likely to occur sometime in the life of an item	$10^{-3} \leq$ Occurrence $L < 10^{-2}$
4. High	Will occur several times in the life of an item	$10^{-2} \leq$ Occurrence $L < 10^{-1}$
5. Very High	Likely to occur frequently	Occurrence $L \geq 10^{-1}$

4.4.2 Fuzzy representations of risk factors

After the determination of the linguistic levels for L and S, one must determine the relevant mathematical expressions using membership functions for fuzzy numbers. However, the determination of a membership function is difficult and complicated. Any shape of a membership function is possible, but the selected shape should be justified by the available information. Bilgic & Turksen (1999) and Ross (2004) discussed several methods of determining the membership functions. It is also believed that in some cases the expressions of membership functions are not the dominant factors in engineering applications (Klir & Yuan, 1995). Chen & Hwang (1992) proposed different scales of linguistic terms for expert assessment. Scale 6 which contains trapezoidal membership functions is adopted to present mathematically the L and S levels of hazards in this research.

A fuzzy number describes the relationship between an uncertain quantity x and a membership function μ, ranging between 0 and 1. A fuzzy set is an extension of traditional set theory (in which x is either a member of set A or not) where x is a member of set A having a certain degree of membership μ. Let the L of a failure be defined by $TPFN_L$ and the S of failure be defined by $TPFN_S$. Table 4.2 demonstrates a five-grade (or granular) qualitative scaling system for L and S. The membership functions of L and S are defined in Table 4.2.

Table 4.2 Linguistic definition of grades (granulars) using TPFNs for L and S

Granular	Qualitative scale for likelihood of risk (Grade of L)	Qualitative scale for severity of risk (Grade of S)	Trapezoidal fuzzy number ($TPFN_S$ or $TPFN_L$)
1	Very low	Extremely unimportant	(0,0,0.1,0.2)
2	Low	Unimportant	(0.1,0.25,0.4)
3	Medium	Neutral	(0.3,0.5,0.7)
4	High	Important	(0.6,0.75,0.9)
5	Very High	Extremely important	(0.8,0.9,1,1)

Trapezoidal memberships of L and S of hazards are represented in Figure 4.2.

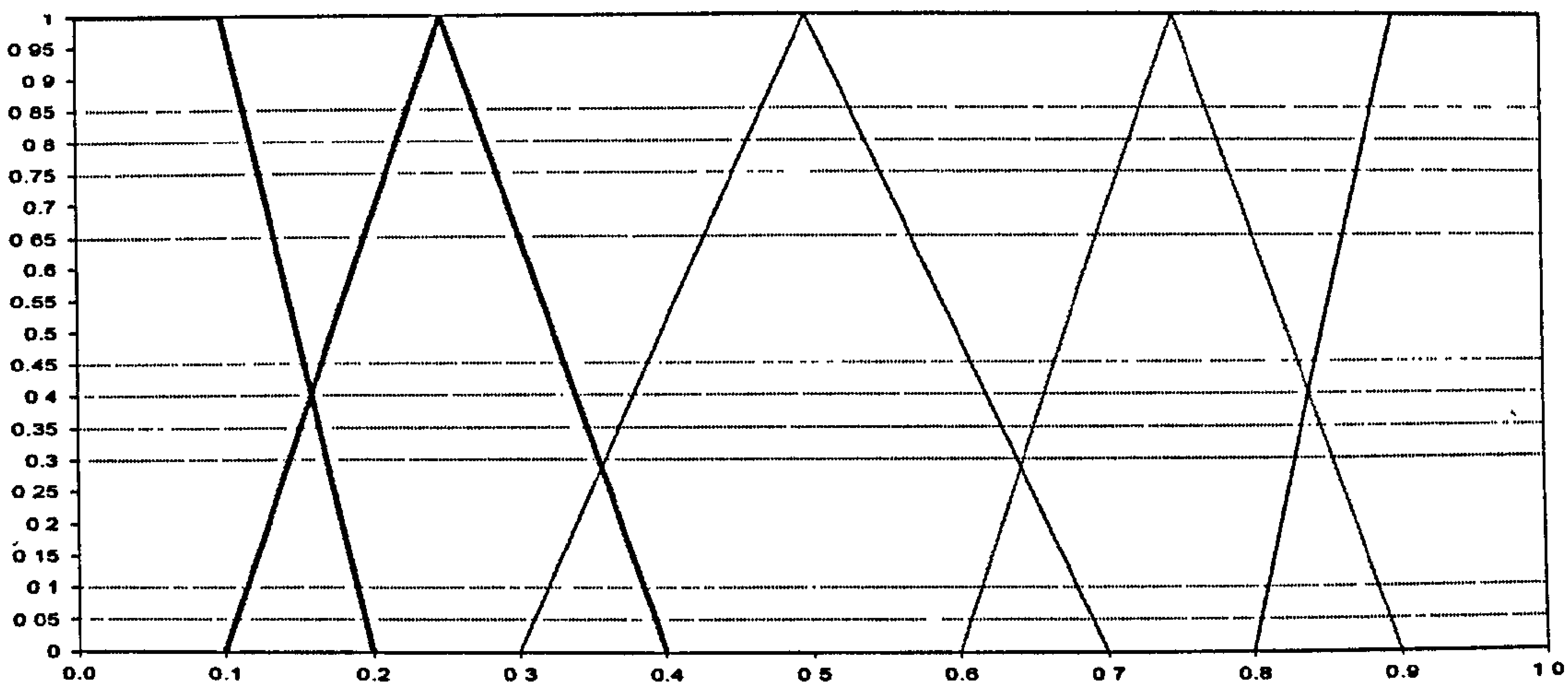


Figure 4.2 Linguistic terms of $TPFN_L$ and $TPFN_S$

Based on the definition of risk (Equation 4.16) and five grades for L and S (Table 4.2), the relative grades of risk are obtained and demonstrated in Table 4.3.

Table 4.3 Linguistic level and explanations used to evaluate risks

Linguistic representation of risk	Description of linguistic values
Very Low	If likelihood is very low and severity extremely unimportant
Low	If likelihood is low and severity is unimportant
Substantial	If the likelihood is medium and severity is neutral
High	If the likelihood is high and severity is important
Very High	If the likelihood is very high and severity is extremely important

According to the definition in Table 4.3, the standard categories of risk level can be determined as follows:

$$R_{very\ Low} = L_{Very\ Low} \otimes S_{Eextremely\ unimportant}$$
$$R_{Low} = L_{Low} \otimes S_{Unimportant}$$
$$R_{Medium} = L_{Medium} \otimes S_{Neutral}$$
$$R_{High} = L_{High} \otimes S_{Important}$$
$$R_{very\ high} = L_{Extermely\ High} \otimes S_{Extermely}$$

where R denotes fuzzy risk variable; L and S denote fuzzy variables of likelihood and severity respectively. Table 4.4 shows the qualitative scales for risk and trapezoidal fuzzy numbers with their centroid values. P is the risk level number.

Table 4.4 Linguistic definitions of granulars using *TPFNs* for risk

Risk level number (P)	Qualitative scale for risk level (Grade of R)	*TPFNs*	Centroid $L_G(P)$
1	Very low: Risk is acceptable	(0,0,0.01,0.04)	0.014
2	Low: Risk is tolerable but should be reduced if it is cost effective	(0.01,0.0625,0.16)	0.077
3	Substantial: Risk must be reduced if it is practicable	(0.09,0.25,0.49)	0.276
4	High: Risk must be reduced	(0.36,0.5625,0.81)	0.577
5	Very high: Risk must be reduced and controlled	(0.64,0.81,1,1)	0.858

The five trapezoidal linguistic terms of risk are illustrated in Figure 4.3.

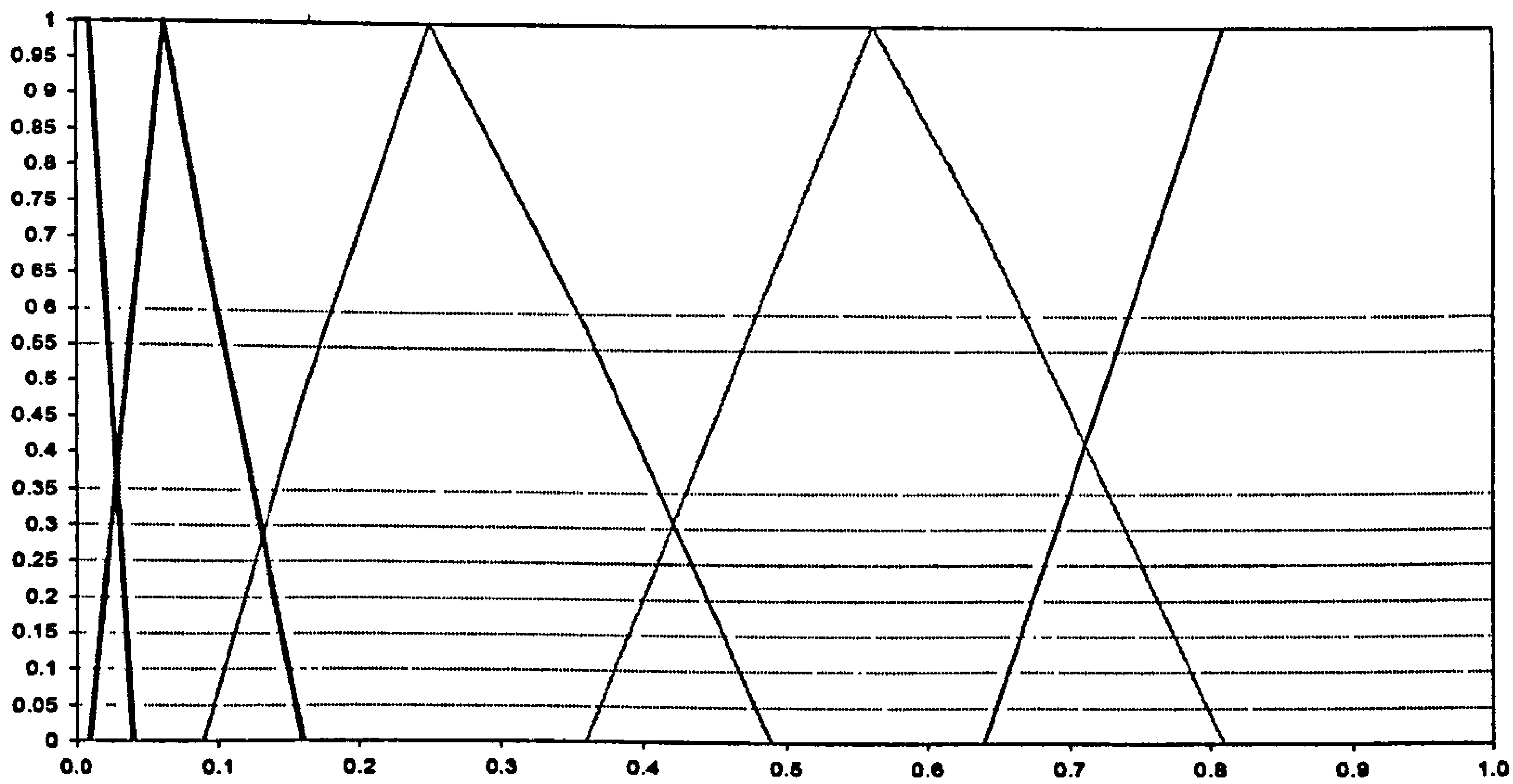


Figure 4.3 Linguistic terms of $TPFN_R$

The risk of failure in the probabilistic realm is the combination of its occurrence probability and severity. When the occurrence probability and severity are assumed to be independent of each other, their combination is equal to the product of the two. Under the same assumption of independence, the fuzzy risk of failure (X) can be calculated as the product of the two fuzzy numbers denoted by L and S as follows:

$$X = TPFN_{LS} = TPFN_L \otimes TPFN_S = (a_L \times a_S, b_L \times b_S, c_L \times c_S, d_L \times d_S) \quad (4.17)$$

For example, if an event has L of $(0.1,0.25,0.4)$(Low) and S of $(0.8,0.9,1,1)$ (Extremely important), the corresponding risk X will be a $TPFN_{LS}$ $(0.08,0.235,0.25,0.4)$. There are five steps to convert $TPFN_{LS}$ into fuzzy risk X_R, a normalized 5 – tuple fuzzy set. These steps are illustrated in Figure 4.4 and explained as follows:

1. Map $TPFN_{LS}$ over $TPFN_R$ (5 grades defined over the universe of discourse of risk).

2. Determine the points where $TPFN_{LS}$ intersects each linguistic term of $TPFN_R$ (Table 4.5).

3. Use a maximum operator if $TPFN_{LS}$ and a linguistic term of $TPFN_R$ intersect at more than one point.

4. Establish a set of intersecting points that defines a non-normalised 5- tuple fuzzy set (e.g., in Figure 4.5, X_R is [0,0.32,1,0.1,0], which is the intersection of X with the membership of grade of risk ($\mu_P, P = 1,2,\cdots,5$) Very low, Low, Medium, High and Very high respectively).

5. Normalise X_R to obtain fuzzy set X^*, where membership value μ_P of X_R is transformed to μ_P^* of X by dividing each μ_P by the cardinality C (sum of all membership values in the fuzzy set) as follows:

$$\mu_p^* = \frac{\mu_P}{\sum_{P=1}^{5} \mu_P} = \frac{\mu_P}{C} \quad (4.18).$$

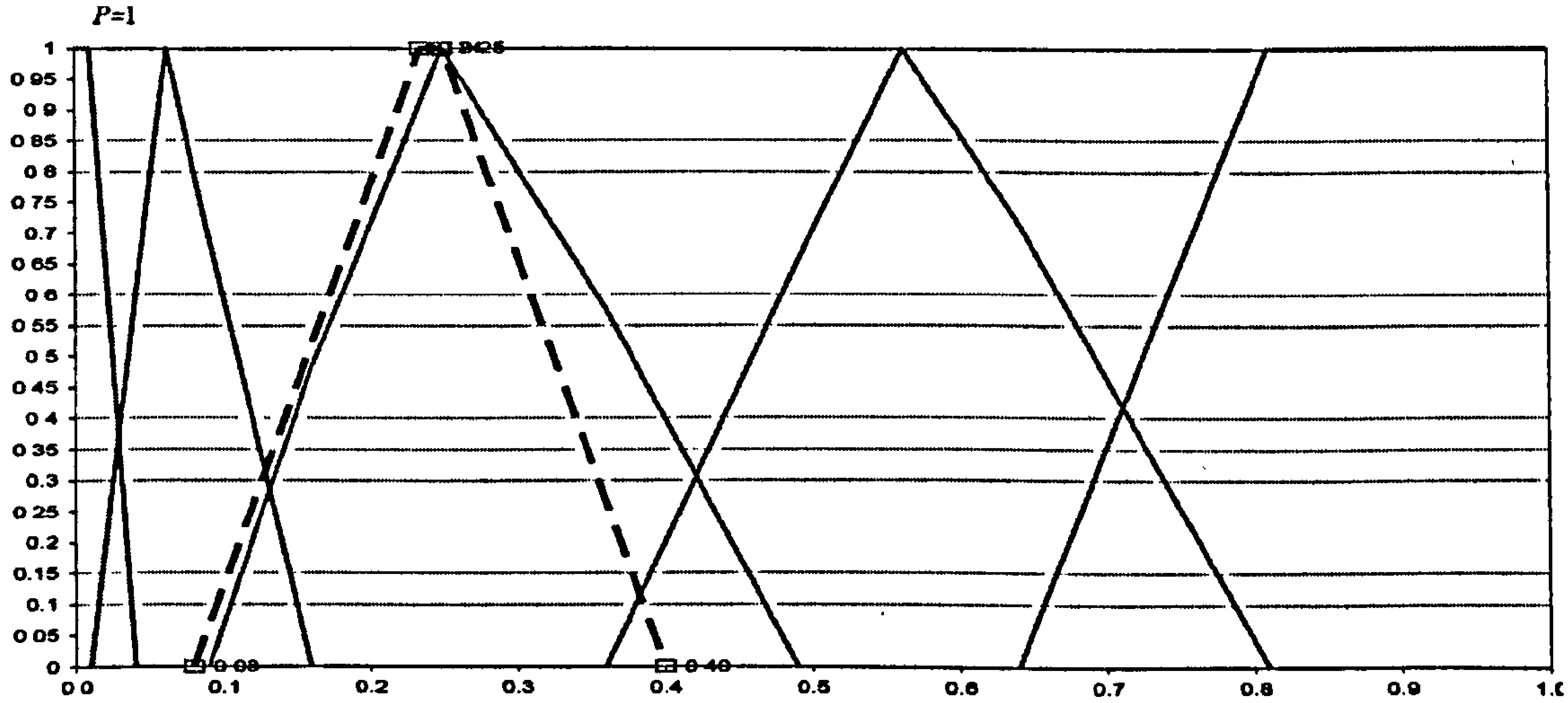


Figure 4.4 Estimating 5-tuple fuzzy set of risk

Table 4.5 Converting fuzzy number $TPFN_{LS}$ into fuzzy risk

$X = TPFN_{LS}$	[0.08,0.235,0.25,0.4]				
P	VL	L	M	H	VH
Inference	0	0.32	1	0.1	0
X_R	[0,0.34,1,0.1,0] (Cardinality, C=1.44) 5- tuple fuzzy set represents membership values to qualitative risk levels				
X^*	[0,0.24,0.69,0.07,0]				

4.5 FAHP

AHP is a methodological approach which implies structuring criteria of multiple options into a system hierarchy, including relative values of all criteria, comparing alternatives for each particular criterion and defining average importance of alternatives. FAHP is employed in this research to obtain the weight of each risk item and synthesise the risks from the bottom level to the top level of a hierarchical risk framework. The earliest work in FAHP appeared in Van Laarhoven & Pedrycz (1983), which compared fuzzy ratios described by triangular membership functions. Later, using the geometric mean, Buckley (1985) determined fuzzy priorities of comparison ratios whose membership functions were trapezoidal. By modifying Buckley's method, Boender et al. (1989) presented a more robust approach to the normalization of local priorities. According to Boender et al. (1989), the triangular approximation of fuzzy operations provides fuzzy solutions with a much smaller spread than Buckley's (1985) method. In 1996, Cheng constructed a fuzzy judgment matrix using continuous judgment scale in which every element can be represented by a positive bounded closed fuzzy number.

Chang (1996) introduced a new approach for handling FAHP with the use of triangular fuzzy numbers for pair-wise comparison scales and the use of extent analysis method for the synthetic extent values of pair-wise comparisons. Cheng (1996) proposed a new algorithm for evaluating naval tactical missile systems using FAHP based on grade values of membership functions. Kahraman et al. (1998) developed a fuzzy weighted evaluation method using objective and subjective measures. Deng (1999) presented a fuzzy approach for dealing with qualitative multi-criteria analysis problems in a simple and straightforward manner.

Lee et al. (1999) introduced the concept of comparison interval scales and proposed a methodology based on stochastic optimization to achieve global consistency and to accommodate the fuzzy nature of the comparison process. Cheng et al. (1999) proposed a new method for evaluating weapon systems using AHP based on linguistic variable weights. Zhu et al. (1999) discussed the extent analysis method and demonstrated some practical examples of FAHP. Leung & Cao (2000) proposed a fuzzy consistency definition with consideration of a tolerance deviation for alternatives in FAHP. More recently, Kuo et al. (2002) developed a decision support system for locating a new convenience store.

Mikhailov (2002) applied the AHP method in conjunction with a fuzzy preference programming approach for partnership selection problems in establishment of virtual enterprises. Other examples of these applications include computer integrated manufacturing systems justification and selection, quality function deployment, catering service companies evaluation, e-marketplace selection, software development strategy selection, new product development process, technology management, project risk evaluation, and global supplier selection (Bozdağ et al., 2003; Kwong & Bai, 2003; Kahraman et al., 2003; Büyüközkan, 2004; Büyüközkan et al., 2004; Erensal et al., 2006; Tüysüz & Kahraman, 2006; Chan & Kumar, 2007).

As noted earlier in this chapter, because the contribution of each risk factor to the overall risk level is different, the weight of the contribution of each risk factor should be taken into consideration in order to represent its relative contribution to the risk level of OGSS. The application of FAHP may solve the problems of risk information loss in the hierarchical process for determining the relative importance of each risk factor in the synthesis process. Therefore, the risk assessment can be progressed from the bottom level of each subsystem hierarchical risk framework to the OGSS level (system level). An advantage of FAHP is its flexibility to be integrated with different techniques, such as FRA techniques in risk analysis. Therefore, FAHP analysis leads to the generation of weighting factors for representing the primary risk factors within each category. Traditional AHP may have the following problems in risk analysis in many situations:

- AHP dose not take into account experts imprecise subjective judgments associated with uncertainty. In practice experts often feel more confident to give judgments by using qualitative descriptors.

- AHP is mainly applied to nearly crisp (non-fuzzy) decisions by a standardised estimation scheme, which adopts crisp numbers to represent the relative importance between alternatives.

FAHP uses a similar framework of AHP to conduct analysis by using fuzzy ratios instead of crisp values. This approach captures the existence of uncertainty in risk assessment. In this chapter the Mikhailov method is employed to obtian weights of risk items at different levels of a hireachical structure.

4.5.1 FAHP estimation procedure

FAHP determines weighting factors by conducting pair-wise comparison. The comparison is based on an estimation scheme, which lists the intensity of importance using qualitative descriptors. Each qualitative descriptor has a corresponding triangular fuzzy number that is employed to transfer experts' judgments into comparisons matrix as follows:

$$\tilde{a}_w = \left(a_w^l, a_w^m, a_w^u\right) \quad (4.19)$$

where a_w^l and a_w^u correspond to the lower and upper values of a range to describe wth qualitative descriptor. a_w^m stands for the most likely value to represent the wth qualitative descriptor. Table 4.6 describes the qualitative descriptors and their corresponding triangular fuzzy numbers (An et al., 2007).

Table 4.6 Estimation scheme

Intensity of importance in qualitative descriptors	Explanations	Triangular fuzzy numbers
Equal Importance (EI)	Two experts or attributes contribute equally to the event	(1,1,2)
Weak Importance (WI)	Experience and judgment slightly favor an expert or attribute over another	(2,3,4)
Strong Importance (SI)	Experience and judgment strongly favor an expert or attribute over another	(4,5,6)
Very Strong Importance (VSI)	An expert or attribute is favored strongly over another	(6,7,8)
Absolute Importance (AI)	The evidence favoring an expert or attribute over another is of the highest order of affirmation	(8,9,9)

4.5.2 Construction of fuzzy pair-wise comparison matrix

Suppose there are m experts in the risk assessment group. The elements in a fuzzy pair-wise comparison can be calculated as follows:

$$\tilde{a}_{i,j} = \left(\frac{1}{m}\right) \otimes \left(e^1_{i,j} \oplus e^2_{i,j} \oplus \cdots e^k_{i,j} \cdots \oplus e^m_{i,j}\right) \tag{4.20}$$

$$\tilde{a}_{j,i} = \frac{1}{\tilde{a}_{i,j}} \tag{4.21}$$

where $\tilde{a}_{i,j}$ is the relative importance formed by comparing event i with event j and $e^k_{i,j}$ stands for the kth expert judgment in a fuzzy number format. A $n \times n$ fuzzy pairwise comparison matrix $\tilde{A}$ can be obtained using Equation 4.22.

$$\tilde{A} = \begin{pmatrix} \tilde{a}_{1,1} & \tilde{a}_{1,2} & \cdots & \tilde{a}_{1,n} \\ \tilde{a}_{2,1} & \tilde{a}_{2,2} & \cdots & \tilde{a}_{2,n} \\ \vdots & \vdots & \tilde{a}_{k,l} & \vdots \\ \tilde{a}_{n,1} & \tilde{a}_{n,2} & \cdots & \tilde{a}_{n,n} \end{pmatrix} \tag{4.22}$$

Weight factors can be calculated by using the geometric mean technique (Saaty, 1990; Tang et al., 2000; Mikhailov, 2004).

$$\tilde{f}_i = \left(\tilde{a}_{i,1} \otimes \tilde{a}_{i,2} \otimes \cdots \tilde{a}_{i,j} \cdots \otimes \tilde{a}_{i,n}\right)^{\frac{1}{n}} = \left(\left(\tilde{a}^l_{i,1} \times \tilde{a}^l_{i,2} \times \cdots \times \tilde{a}^l_{i,n}\right)^{\frac{1}{n}}, \left(\tilde{a}^m_{i,1} \times \tilde{a}^m_{i,2} \times \ldots \times \tilde{a}^m_{i,n}\right)^{\frac{1}{n}}, \left(\tilde{a}^u_{i,1} \times \tilde{a}^u_{i,2} \times \cdots \times \tilde{a}^u_{i,n}\right)^{\frac{1}{n}}\right) \tag{4.23}$$

$$\tilde{w}_i = \frac{\tilde{f}_i}{\tilde{f}_1 \oplus \tilde{f}_2 \oplus \cdots \tilde{f}_i \cdots \oplus \tilde{f}_n} \quad (4.24)$$

where $\tilde{f}_i$ is the geometric mean of the ith row in the fuzzy pair-wise comparison matrix and $\tilde{w}_i$ is the fuzzy weight factor of the ith event. The output of the geometric mean method are triangular fuzzy weight factors, and a centroid defuzzification is adopted to convert a triangular fuzzy weight factor into a corresponding crisp weight factor in which FAHP employs a defuzzification approach obtained using Equation 4.25. The triangular fuzzy weight factor $\tilde{w}_i = (a_i^l, a_i^m, a_i^u)$ can be defuzzified as follows:

$$DF\tilde{w}_i = \frac{\int \mu_i(x) x dx}{\int \mu_i(x)} \quad (4.25)$$

where $DF\tilde{w}_i$ is the defuzzified mean value of the fuzzy weight factor. w_i can be calculated using Equation 4.26.

$$w_i = \frac{DF\tilde{w}_i}{\sum_{i=1}^{n} DF\tilde{w}_i} \quad (4.26)$$

In this research, triangular fuzzy numbers are used for weight modelling and trapezoidal fuzzy numbers are selected for other modelling. Table 4.6 which contains triangular fuzzy numbers is used for pair-wise comparison of two experts or attributes. This Table has been used in many research papers for weight modelling (Mon et al., 1994; Cheng, 1997; Mikhailov, 2004; An, 2007; An et al., 2007). Therefore, it is used for the same purpose in this research. Table 4.2 which contains trapezoidal fuzzy numbers is selected for identifying the importance level of an item, event or attribute.

4.6 Risk aggregation

Figure 4.5 illustrates the basic building blocks of the proposed hierarchical structural model for the risk aggregation. Each risk item is partitioned into its contributory factors, which are also risk items, and each of those can be further partitioned into lower level contributory factors. A unit that consists of a risk factor ("parent") and its contributory factors ("children") is called "family". A risk unit without children is called basic risk item, while the term *risk item* is used for all elements with offspring. The notation used for a risk item is $X_{i,j}^{k}$, where j is the ordinal number of the risk item X in the current generation; i is the ordinal number of the parent (in the previous generation); and k is the generation order of X. The indices i,j,k are used for risk item attributes. The factors $L_{i,j}^{k}$ and $S_{i,j}^{k}$ denote likelihood and severity (respectively) for the risk item $X_{i,j}^{k}$.

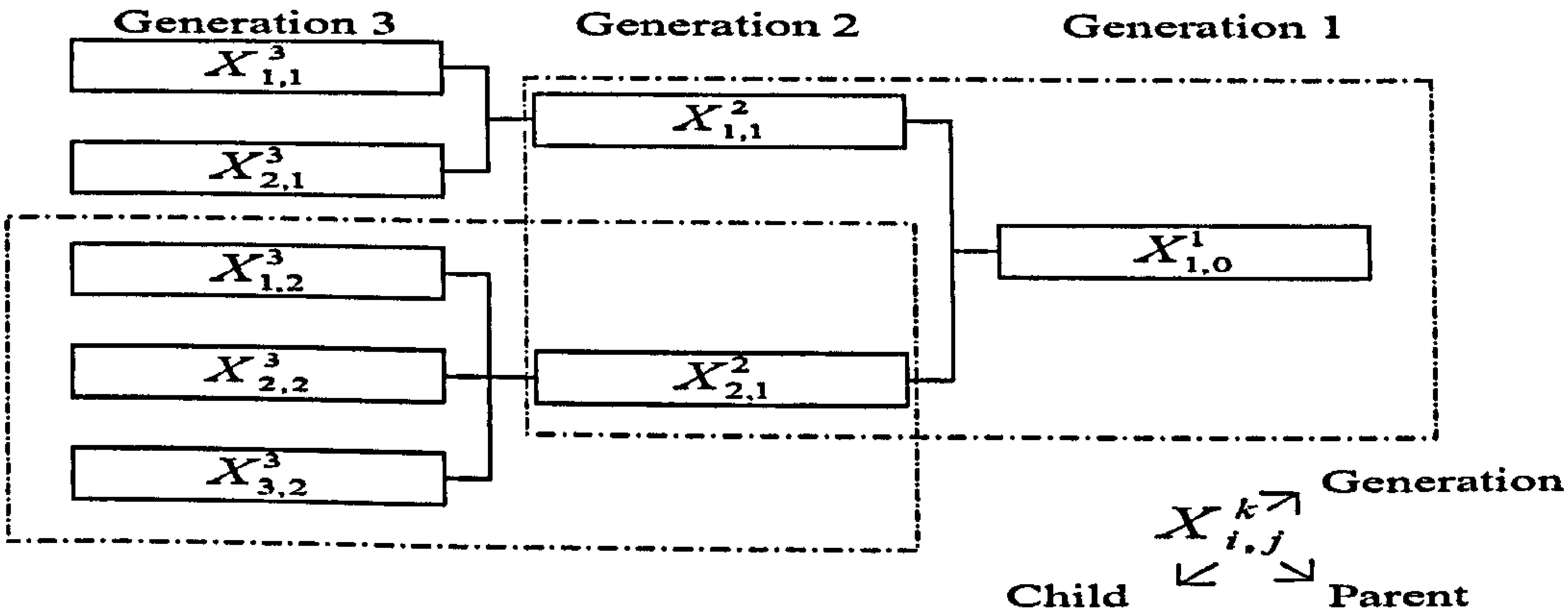


Figure 4.5 A hierarchical structure for the estimation of aggregative risk

Figure 4.5 shows a general case in which weights are assigned to each risk item. The notation used is $w_{i,j}^{k}$, which denotes the weight of $X_{i,j}^{k}$ relative to its siblings. Saaty (2001) described in detail the AHP to derive the weights. These weights are normalized to sum unity, such that in any generation k, for n siblings with parent i, a set of weights can be written as follows:

$$w_{i,j}^{k} = \left\lfloor w_{1,i}^{k}, w_{2,i}^{k}, \ldots, w_{n,i}^{k} \right\rfloor \text{ where } \sum_{i=1}^{n} w_{i,j}^{k} = 1 \tag{4.27}$$

The process of evaluating aggregative risk in a "family" with an aggregative structure is described using the family (Figure 4.5) with $X_{1,2}^{2}$ (parent) and $X_{2,1}^{3}$, $X_{2,2}^{3}$, $X_{2,3}^{3}$ (children), for example. For each of the sibling risk items, the likelihood *(L)* and severity *(S)* are assigned from the 5-grade scaling system (Table 4.2). $TPFN_{LS}(X)$ is the product of two fuzzy numbers $TPFN_L$ and $TPFN_S$ (Equation 4.17), which is then mapped over $TPFN_R$ to obtain the 5-tuple fuzzy set X_L (a non-normalized fuzzy set for risk). X_L is then normalized to obtain the 5-tuple fuzzy sets representing the risk contribution of each of the siblings towards their parent. For ease of manipulation these 5-tuple sets can be arranged in a fuzzy assessment matrix, which is a 3×5 matrix $F\begin{pmatrix} \mu_1(X_{2,1}^3) & \mu_2(X_{2,1}^3) & \mu_3(X_{2,1}^3) & \mu_4(X_{2,1}^3) & \mu_5(X_{2,1}^3) \\ \mu_1(X_{2,2}^3) & \mu_2(X_{2,2}^3) & \mu_3(X_{2,2}^3) & \mu_4(X_{2,2}^3) & \mu_5(X_{2,2}^3) \\ \mu_1(X_{2,3}^3) & \mu_2(X_{2,3}^3) & \mu_3(X_{2,3}^3) & \mu_4(X_{2,3}^3) & \mu_5(X_{2,3}^3) \end{pmatrix}$. FAHP is then applied, weights $w_{2,1}^3$, $w_{2,2}^3$ and $w_{2,3}^3$ are evaluated and arranged into a 3-member vector. The aggregative risk (or parent) of the three siblings is the cross product of the weight vector and the assessment matrix, resulting in a 5-tuple fuzzy set $X_{2,1}^2$.

$$X_{1,2}^2 = [w_{2,1}^3, w_{2,2}^3, w_{2,3}^3]\begin{pmatrix} \mu_1(X_{2,1}^3) & \mu_2(X_{2,1}^3) & \mu_3(X_{2,1}^3) & \mu_4(X_{2,1}^3) & \mu_5(X_{2,1}^3) \\ \mu_1(X_{2,2}^3) & \mu_2(X_{2,2}^3) & \mu_3(X_{2,2}^3) & \mu_4(X_{2,2}^3) & \mu_5(X_{2,2}^3) \\ \mu_1(X_{2,3}^3) & \mu_2(X_{2,3}^3) & \mu_3(X_{2,3}^3) & \mu_4(X_{2,3}^3) & \mu_5(X_{2,3}^3) \end{pmatrix} \quad (4.28)$$

where $\mu_P(X_{1,2}^2) = [\mu_1(X_{1,2}^2), \mu_2(X_{1,2}^2), \mu_3(X_{1,2}^2), \mu_4(X_{1,2}^2), \mu_5(X_{1,2}^2)]$ is the membership function of the aggregated risk with respect to the 5-grade risk scale. It should be noted that the process of evaluating L and S and mapping the product risk onto the 5-grade risk scale is necessary only for basic risk items, i.e. those risk items, which do not have children. All subsequent risk aggregations from one generation to the next are determined by applying Equation 4.28 and using the appropriate relative weights. The rate of final aggregative risk for top attribute $X_{0,1}^1$ can be obtained using Equation 4.29.

$$R = \sum_{P=1}^{5} L_G(P) \times \mu_P(X_{0,1}^1) \quad (4.29)$$

R is calculated as a dot product of vector $L_G(P)$ and the aggregation fuzzy number for $X_{0,1}^1$, where $L_G(P)$ (Table 4.3) is the 5-tuple vector representing the centroid values of linguistic risk levels. Consequently it is useful to use notation that distinguishes between basic and non basic risk items. In the remainder of this paper, the notation for a basic risk item will include a star at the generation index, i.e., if item $X_{2,3}^3$ is a basic risk item, it will be denoted by $X_{2,3}^{3*}$.

4.7 Risk updating

The theory of evidence was first generated by Dempster (1967) and further developed by Shafer (1976); it is often referred to as Dempster-Shafer theory of evidence or D-S theory. The D-S theory was originally used for information aggregation in expert systems as an approximate reasoning tool (Lopez de Mantaras, 1990). Subsequently it has been used as an aid to decision making under conditions of uncertainty (Yager, 2004).

In the 1990s, ER was developed to deal with Multiple Criteria Decision Making (MCDM) problems under uncertainty based on the D-S theory. The use of ER as a decision making tool has been widely reported. The ER approach developed particularly for MCDM problems with both qualitative and quantitative criteria under uncertainty utilises individuals' knowledge, expertise and experience in the forms of belief functions (Wang et al., 1995; Yang & Xu, 2002). The ER rule of combination defines how to combine evidence obtained from two or more sources. Let A represent the set of the five safety expressions, which have been synthesized by two subsets A_1 and A_2 from two different assessors. Then, A, A_1 and A_2 can separately be expressed by:

A = {α^1 "Very low", α^2 "Low", α^3 "Medium", α^4 "High", α^5 "Very high"}
A_1 = {α^1_1 "Very low", α^2_1 "Low", α^3_1 "Medium", α^4_1 "High", α^5_1 "Very high"}
A_2 = {α^1_2 "Very low", α^2_2 "Low", α^3_2 "Medium", α^4_2 "High", α^5_2 "Very high"}

The normalized relative weights of two safety assessors in the safety evaluation process are given as w_1 and w_2 $(w_1 + w_2 = 1)$.

Suppose M_1^m and $M_2^m (m = 1,2,3,4 \text{ or } 5)$ are probability masses (or weighted belief degrees) to which the estimates A_1 and A_2 support the hypothesis that the safety evaluation is confirmed to the five safety expressions. Then, M_1^m and M_2^m can be obtained as follows:

$$M_1^m = w_1 \alpha_1^m, \quad M_2^m = w_2 \alpha_2^m \tag{4.30}$$

Let $H_1 = 1 - w_1 \sum_{m=1}^{4} \alpha_1^m$ and $H_2 = 1 - w_2 \sum_{m=1}^{4} \alpha_2^m$ (4.31)

H_1 and H_2 are regarded as remaining probability masses unassigned to any of the linguistic safety expressions. The terms H_1 and H_2 can be decomposed as follows (Yang & Xu, 2002):

$$H_1 = \overline{H}_1 + \widetilde{H}_1 \text{ and } H_2 = \overline{H}_2 + \widetilde{H}_2 \tag{4.32}$$

where $\overline{H}_1 = 1 - w_1$ and $\overline{H}_2 = 1 - w_2$ represent the degree to which the other assessors can play a role in the assessment while

$$\widetilde{H}_1 = w_1 \, (1 - \sum_{m=1}^{5} a_1^m) = w_1 \, [1 - (\alpha^1{}_1 + \alpha^2{}_1 + \alpha^3{}_1 + \alpha^4{}_1 + \alpha^5{}_1)] \tag{4.33}$$

and

$$\widetilde{H}_2 = w_2 (1 - \sum_{m=1}^{5} a_2^m) = w_2 \, [1 - (\alpha^1{}_2 + \alpha^2{}_2 + \alpha^3{}_2 + \alpha^4{}_2 + \alpha^5{}_2)] \tag{4.34}$$

represent the possible incompleteness in the estimates A_1 and A_2.

Suppose $a^{m\prime}$ (m = *1, 2, 3, 4* or *5*) represents the combined probability mass to which the safety evaluation is confirmed to the five safety expressions as a result of the synthesis of the judgments produced by assessors 1 and 2. Suppose $H_U{}'$ represents the remaining belief degree unassigned to any of the safety expression as a result of the synthesis of the judgments produced by assessors 1 and 2. The evidential reasoning algorithm can be stated as follows:

$$K = [1 - \sum_{T=1}^{5} \sum_{\substack{R=1 \\ R \neq T}}^{5} M_1^T M_2^R]^{-1} \tag{4.35}$$

$$a^{m\prime} = K(M_1^m M_2^m + M_1^m H_2 + M_2^m H_1) \tag{4.36}$$

$$\overline{H}_U{}' = K \, (\overline{H}_1 \, \overline{H}_2) \tag{4.37}$$

$$\widetilde{H}_U{}' = K \, (\widetilde{H}_1 \, \widetilde{H}_2 + \widetilde{H}_1 H_2 + H_1 \widetilde{H}_2) \tag{4.38}$$

After the above aggregation, the combined degrees of belief a^m and normalised remaining belief H_U which represents the incompleteness in the overall assessment are generated by assigning $\overline{H}_U'$ back to the five safety expressions using the following normalization process:

$$a^m = a^{m\prime}/(1-\overline{H}_U') \quad (m = 1, 2, 3, 4 \text{ or } 5) \tag{4.39}$$

$$H_U = \tilde{H}_U'/(1-\overline{H}_U') \tag{4.40}$$

The above process can be repeated if more estimates need to be synthesised at one level or between different levels in a hierarchical framework. In this way, multiple subsets can be synthesised using the ER algorithm.

4.8 Validation of fuzzy aggregative risk assessment methodology

When a new methodology is developed, it requires a careful testing to ensure its robust which is especially important and desirable when subjective elements are involved in the methodology generated. There are several widely-accepted validation methods available for testing a new methodology. Sensitivity analysis shows how sensitive the outcome is to changes in inputs. The changes may be variations of L and S or the weights assigned to the risk items at different attribute levels. If the methodology is sound and logical, then the sensitivity analysis must at least concur with the following three axioms:

Axiom1. A slight increment/decrement in L and S of each basic risk item should result in the effect of a relative increase and decrease of Final Aggregative Risk (FAR) respectively.

Axiom2. If L and S of x basic risk item s are increased to one higher linguistic judgment, the FAR with such basic risk items must be greater than the FAR with a set of $(x-y)$ such basic risk items where $y \in x$.

Axiom3. If L and S of x basic risk item s are decreased to one lower linguistic judgment, the FAR with such basic risk items must be smaller than the FAR with a set of $(x-y)$ such basic risk items where $y \in x$.

4.9 Case study

The following test case is used to illustrate the assessment of risks in an OGSS.

4.9.1 Developing an aggregative risk framework

Two aggregative risk frameworks of OGSS were developed in Chapter 3. One of those frameworks (framework for a compressor gas leakage) is adopted in this section to demonstrate the application of the proposed methodology.

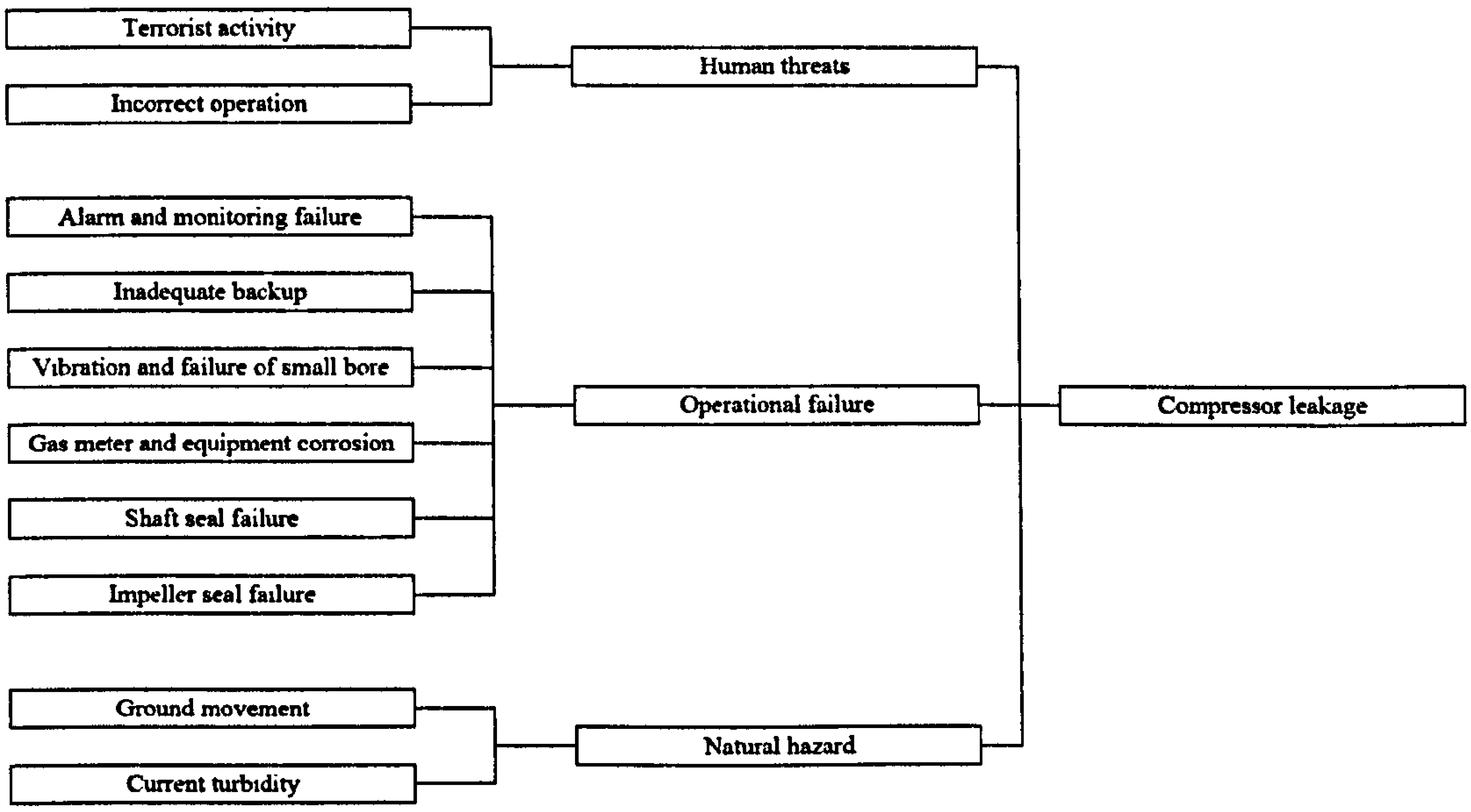


Figure 4.6 Hierarchical structure of aggregative risk model of compressor gas leakage

Figure 4.6 represents a hierarchical structure model of aggregative risk involving three major attributes: human threats ($X^2{}_{1,1}$), operational failure ($X^2{}_{1,2}$) and natural hazard ($X^2{}_{1,3}$) at attribute level-2. The level-2 attributes are further divided into basic risk items, for example the human threat risk is divided into terrorist activity ($X^{3*}_{1,1}$) and incorrect operation ($X^{3*}_{1,2}$). The operational failure is divided into alarm and monitoring failure ($X^{3*}_{2,1}$), inadequate backup ($X^{3*}_{2,2}$), vibration and failure of small bore ($X^{3*}_{2,3}$), gas meter and equipment corrosion ($X^{3*}_{2,4}$), shaft seal failure ($X^{3*}_{2,5}$) and impeller seal failure ($X^{3*}_{2,6}$). Similarly the natural hazard at level-1 is divided into two different basic risk items: ground movement ($X^{3*}_{3,1}$) and current turbidity ($X^{3*}_{3,2}$).

4.9.2 FRA

An expert panel can determine the grades of L and S for basic risk item s. It should be noted that there is no data available regarding S of occurrence. If L of a basic risk item is known, then it can be converted into its corresponding linguistic terms using Table 4.1. For example, L for $X^{3*}_{2,5}$ is 3.5×10^{-4}, this value can be converted into its corresponding L grade of 2 or linguistic term of Low by using Table 4.1. The grades of L and S for the basic risk items together with the weights of attributes at level-2 and level-3 of Figure 4.6 are demonstrated in Table 4.7 by using 5 grades of L and S which are provided in Table 4.2

Table 4.7 Structure model of leakage in gas compressor

FAR	Attributes in level-2	Attributes in level-3	Weights of attributes in level-2	Weights of attribute in level-3	Grade L	Grade S
$X^1_{0,1}$						
	$X^2_{1,1}$		$w^2_{1,1}$			
		$X^{3*}_{1,1}$		$w^{3*}_{1,1}$	2	4
		$X^{3*}_{1,2}$		$w^{3*}_{1,2}$	1	5
	$X^2_{1,2}$		$w^2_{1,2}$			
		$X^{3*}_{2,1}$		$w^{3*}_{2,1}$	2	4
		$X^{3*}_{2,2}$		$w^{3*}_{2,2}$	1	3
		$X^{3*}_{2,3}$		$w^{3*}_{2,3}$	1	2
		$X^{3*}_{2,4}$		$w^{3*}_{2,4}$	3	2
		$X^{3*}_{2,5}$		$w^{3*}_{2,5}$	2	2
		$X^{3*}_{2,6}$		$w^{3*}_{2,6}$	2	2
	$X^2_{1,3}$		$w^2_{1,3}$			
		$X^{3*}_{3,1}$		$w^{3*}_{3,1}$	2	5
		$X^{3*}_{3,2}$		$w^{3*}_{3,2}$	2	4

The risks of basic risk items are evaluated in terms of the aforementioned criteria L and S by using Equation 4.16. Table 4.8 presents the risks of them in the form of $TPFN_{LS}$.

Table 4.8 Risk of basic risk items

$X_{i,j}^{\bullet}$	L	S	$TPFN_L$				$TPFN_S$				$TPFN_{LS}$			
$X_{1,1}^{3\bullet}$	2	4	0.1	0.25	0.25	0.4	0.6	0.75	0.75	0.9	0.06	0.19	0.19	0.36
$X_{1,2}^{3\bullet}$	1	5	0	0	0.1	0.2	0.8	0.9	1	1	0.00	0.00	0.10	0.20
$X_{2,1}^{3\bullet}$	2	4	0.1	0.25	0.25	0.4	0.6	0.75	0.75	0.9	0.06	0.19	0.19	0.36
$X_{2,2}^{3\bullet}$	1	3	0	0	0.1	0.2	0.3	0.5	0.5	0.7	0.00	0.00	0.05	0.14
$X_{2,3}^{3\bullet}$	1	2	0	0	0.1	0.2	0.1	0.25	0.25	0.4	0.00	0.00	0.03	0.08
$X_{2,4}^{3\bullet}$	3	2	0.3	0.5	0.5	0.7	0.1	0.25	0.25	0.4	0.03	0.13	0.13	0.28
$X_{2,5}^{3\bullet}$	2	2	0.1	0.25	0.25	0.4	0.1	0.25	0.25	0.4	0.01	0.06	0.06	0.16
$X_{2,6}^{3\bullet}$	2	2	0.1	0.25	0.25	0.4	0.1	0.25	0.25	0.4	0.01	0.06	0.06	0.16
$X_{3,1}^{3\bullet}$	2	5	0.1	0.25	0.25	0.4	0.8	0.9	1	1	0.08	0.23	0.25	0.40
$X_{3,2}^{3\bullet}$	2	4	0.1	0.25	0.25	0.4	0.6	0.75	0.75	0.9	0.06	0.19	0.19	0.36

The intersection results of all the evaluated risks over $TPFN_R$ are presented in Table 4.9.

Table 4.9 Intersection results of all the evaluated risks over $TPFN_R$

$TPFN_{LS}$				VL	L	M	H	VH
0.06	0.19	0.19	0.36	0	0.43	0.83	0	0
0.00	0.00	0.10	0.20	1	1	0.45	0	0
0.06	0.19	0.19	0.36	0	0.43	0.83	0	0
0.00	0.00	0.05	0.14	1	0.92	0.2	0	0
0.00	0.00	0.03	0.08	1	0.7	0	0	0
0.03	0.13	0.13	0.28	0.08	0.65	0.62	0	0
0.01	0.06	0.06	0.16	0.37	1	0.28	0	0
0.01	0.06	0.06	0.16	0.37	1	0.28	0	0
0.08	0.23	0.25	0.40	0	0.33	1	0.1	0
0.06	0.19	0.19	0.36	0	0.43	0.83	0	0

The evaluated risks are subsequently normalized using Equation 4.18 and the results are presented in Table 4.10.

Table 4.10 Normalised fuzzy risks

$X_{i,j}^{*}$	VL	L	M	H	VH
$X_{1,1}^{3*}$	0.00	0.34	0.66	0.00	0.00
$X_{1,2}^{3*}$	0.41	0.41	0.18	0.00	0.00
$X_{2,1}^{3*}$	0.00	0.34	0.66	0.00	0.00
$X_{2,2}^{3*}$	0.47	0.43	0.09	0.00	0.00
$X_{2,3}^{3*}$	0.59	0.41	0.00	0.00	0.00
$X_{2,4}^{3*}$	0.06	0.48	0.46	0.00	0.00
$X_{2,5}^{3*}$	0.22	0.61	0.17	0.00	0.00
$X_{2,6}^{3*}$	0.22	0.61	0.17	0.00	0.00
$X_{3,1}^{3*}$	0.00	0.23	0.70	0.07	0.00
$X_{3,2}^{3*}$	0.00	0.34	0.66	0.00	0.00

4.9.3 FAHP

Fuzzy set theory and AHP are used to estimate the weights of all the risk items at different attribute levels. Table 4.6 is employed to carry out the pair-wise comparison. Five linguistic terms are used ranging from EI to AI. A 3×3 pair-wise comparison matrix is developed to obtain the weights of the level-2 risk items (human threats ($X^2{}_{1,1}$), operational failure ($X^2{}_{2,1}$) and natural hazard ($X^2{}_{3,1}$)). $\tilde{A}$ is the pair-wise comparison matrix expressing the quantified judgment with regard to the relative importance of the level-2 risk items. For example, risk items of $X^2{}_{2,1}$ and $X^2{}_{3,1}$ were compared by three safety analysts. Two of them estimated the comparison of $X^2{}_{2,1}$ with $X^2{}_{3,1}$ as SI which corresponds to fuzzy number of $(4,5,6)$. The third analyst gave the comparison of $X^2{}_{2,1}$ with $X^2{}_{3,1}$ as VSI which corresponds to fuzzy number of

$(6,7,8)$. Using Equation 4.21, the elements of $\tilde{a}_{13}$ and $\tilde{a}_{31}$ in $\tilde{A}$ can be obtained as follows:

$$\tilde{a}_{13} = \frac{1}{3}((4,5,6)\oplus(4,5,6)\oplus(6,7,8)) = (4.66,5.66,6.66)$$

$$\tilde{a}_{31} = \frac{1}{\tilde{a}_{13}} = \frac{1}{(4.66,5.66,6.66)} = (0.15,0.176,0.215)$$

A 3×3 fuzzy pairwise comparison matrix $\tilde{A}$ can be constructed as follows:

$$\tilde{A} = \begin{array}{c} \\ X^2_{1,1} \\ X^2_{2,1} \\ X^2_{3,1} \end{array}\begin{array}{c} \begin{array}{ccc} X^2_{1,1} & X^2_{2,1} & X^2_{3,1} \end{array} \\ \begin{bmatrix} (1,1,1) & (1,1,2) & (1.66,2.33,3.33) \\ (0.5,1,1) & (1,1,1) & (4.66,5.66,6.66) \\ (0.3,0.43,0.6) & (0.15,0.176,0.215) & (1,1,1) \end{bmatrix} \end{array}$$

Each attribute weight at level-2 of the hierarchy can be calculated by using Equations 4.23 and 4.24. For example, $\tilde{w}^2_{1,1}$ is calculated as follows:

$$\tilde{f}_{X^2_{1,1}} = ((1,1,1)\otimes(1,1,2)\otimes(1.66,2.33,3.33))^{\frac{1}{3}} = \left((1\times1\times1.66)^{\frac{1}{3}},(1\times1\times2.33)^{\frac{1}{3}},(1\times2\times3.33)^{\frac{1}{3}}\right)$$

$$\tilde{f}_{X^2_{1,1}} = (1.18,1.32,1.86),\ \tilde{f}_{X^2_{2,1}} = (1.32,1.77,1.86),\ \tilde{f}_{X^2_{3,1}} = (0.35,0.426,0.5)$$

$$\tilde{w}^2_{1,1} = \frac{\tilde{f}_{X^2_{1,1}}}{\tilde{f}_{X^2_{1,1}} + \tilde{f}_{X^2_{2,1}} + \tilde{f}_{X^2_{3,1}}} = \frac{(1.18,1.32,1.86)}{(2.86,3.51,4.22)} = \left(\frac{1.18}{4.22},\frac{1.32}{3.51},\frac{1.86}{2.86}\right) = (0.28,0.37,0.65)$$

$\tilde{w}^2_{1,1}$ can be converted into a crisp value by using Equation 4.25 as follows:

$$DF_{\tilde{w}^2_{1,1}} = \frac{0.28+0.37+0.65}{3} = 0.43$$

In a similar way, $DF_{\tilde{w}^2_{2,1}}$ and $DF_{\tilde{w}^2_{3,1}}$ are found to be 0.48 and 0.12 respectively. The normalised weight of $X^2_{1,1}$, $w^2_{1,1}$ is obtained using Equation 4.26 as follows:

$$w^2_{1,1} = \frac{0.43}{0.43+0.48+0.12} = 0.417$$

The weights of the other attributes at level-2 and level-3 of the hierarchy can be obtained by repeating the above process. The weights of all the risk items at different levels of the hierarchical risk framework are presented in Table 4.11.

Table 4.11 Weights of risk items at different attribute levels

Weights of attributes in level-2	Weights of attributes in level-3	Defuzzified weights of attributes in level-2	Defuzzified weights of attributes in level-3	Normalized weights of attributes in level-2	Normalized weights of attributes in level-3
$w_{1,1}^{2}$		0.43		0.417	
	$w_{1,1}^{3*}$		0.86		0.835
	$w_{1,2}^{3*}$		0.17		0.165
$w_{1,2}^{2}$		0.48		0.466	
	$w_{2,1}^{3*}$		3.61		0.47
	$w_{2,2}^{3*}$		0.92		0.121
	$w_{2,3}^{3*}$		0.47		0.062
	$w_{2,4}^{3*}$		0.79		0.1
	$w_{2,5}^{3*}$		0.98		0.13
	$w_{2,6}^{3*}$		0.9		0.117
$w_{1,3}^{2}$		0.12		0.117	
	$w_{3,1}^{3*}$				0.74
	$w_{3,2}^{3*}$				0.26

4.9.4 Aggregation

The fuzzy assessment matrices for the risk items of attribute level-2 can be established for $X_{1,1}^{2}, X_{1,2}^{2}$ and $X_{1,3}^{2}$ individually. For example, for $X_{1,1}^{2}$, the risk items involved are $X_{1,1}^{3*}$ and $X_{1,2}^{3*}$. The value of each risk item is estimated from Table 4.2, and then Figure 4.5 is used to estimate the level of risk for each item. Thus a fuzzy assessment matrix $F(X_{1,1}^{2})$ can be obtained as follows:

$$F(X_{1,1}^{2})=\begin{bmatrix}(R(L_{1,1}^{3}\otimes S_{1,1}^{3},1)=\mu_{1}(X_{1,1}^{3*})),\ldots,(R(L_{1,1}^{3}\otimes S_{1,1}^{3},5)=\mu_{5}(X_{1,1}^{3*})) \\ (R(L_{1,2}^{3}\otimes S_{1,2}^{3},1)=\mu_{1}(X_{1,2}^{3*})),\ldots,(R(L_{1,2}^{3}\otimes S_{1,2}^{3},5)=\mu_{5}(X_{1,2}^{3*}))\end{bmatrix}\begin{matrix}X_{1,1}^{3*}\\X_{1,2}^{3*}\end{matrix} \quad (4.41)$$

Similarly, the fuzzy assessment matrices for $F(X_{1,2}^{2})$ and $F(X_{1,3}^{2})$ can be formed for the corresponding attributes $X_{1,2}^{2}$ and $X_{1,3}^{2}$ respectively. Now the first stage aggregative assessment of gas leakage in compressor can be evaluated for attribute $X_{1,1}^{2}$ as follows:

$$\begin{aligned}&[w_{1,1}^{3},w_{2,1}^{3}]_{1\times 2}\times F(X_{1,1}^{2})_{2\times 5}=[(w_{1,1}^{3}\times\mu_{1}(X_{1,1}^{3*})+w_{1,2}^{3}\times\mu_{1}(X_{1,2}^{3*})),\ldots,\\&(w_{1,1}^{3}\times\mu_{5}(X_{1,1}^{3*})+w_{1,2}^{3}\times\mu_{5}(X_{1,2}^{3*}))]\end{aligned} \quad (4.42)$$

Table 4.12 presents the first stage of aggregative calculation.

Table 4.12 Result of first stage of aggregative risk assessment

VL	L	M	H	VH	w_{ij}^{3*}	X_{ij}^{2}	VL	L	M	H	VH
0.00	0.34	0.66	0.00	0.00	0.835	$X_{1,1}^{2}$	0.067	0.353	0.580	0.000	0.000
0.41	0.41	0.18	0.00	0.00	0.165						
0.00	0.34	0.66	0.00	0.00	0.470	$X_{1,2}^{2}$	0.155	0.436	0.409	0.000	0.000
0.47	0.44	0.09	0.00	0.00	0.121						
0.59	0.41	0.00	0.00	0.00	0.062						
0.06	0.48	0.46	0.00	0.00	0.100						
0.22	0.61	0.17	0.00	0.00	0.130						
0.22	0.61	0.17	0.00	0.00	0.117						
0.00	0.23	0.70	0.07	0.00	0.740	$X_{1,3}^{2}$	0.000	0.259	0.689	0.052	0.000
0.00	0.34	0.66	0.00	0.00	0.260						

The second stage of aggregative calculation is performed in a similar way. Table 4.13 shows the quantification the second stage of aggregative calculation.

Table 4.13 The second stage of aggregative risk assessment

X_{ij}^{2}	VL	L	M	H	VH	w_{ij}^{2}		VL	L	M	H	VH
$X_{1,1}^{2}$	0.067	0.353	0.580	0.000	0.000	0.417	$X_{0,1}^{1}$	0.100	0.381	0.513	0.006	0.000
$X_{1,2}^{2}$	0.155	0.436	0.409	0.000	0.000	0.466						
$X_{1,3}^{2}$	0.000	0.259	0.689	0.052	0.000	0.117						

The rate of FAR for compressor gas leakage is shown in Table 4.14. It can be obtained by using Equation 4.29.

Table 4.14 Result of final aggregative risk assessment of compressor gas leakage

	VL	L	M	H	VH
$X^1_{0,1}$	0.100	0.381	0.513	0.006	0.000
$L_G(P)$	0.014	0.077	0.276	0.577	0.858
X	0.175				

The overall risk of compressor gas leakage is 0.175. This belongs to the substantial risk category (Table 4.4). It means that the risk must be reduced if practicable. The result of aggregative calculation for the OGSS can be obtained by aggregating the risks of all the subsystems. The risks of all the subsystems are calculated and demonstrated in Appendix 2. The value of FAR for the OGSS is obtained and shown in Table 4.15.

Table 4.15 Result of aggregative risk assessment of an OGSS

Risks of subsystems	VL	L	M	H	VH	*Weights of subsystems*	FAR of the OGSS	VL	L	M	H	VH
Risk of gas holder	0.270	0.449	0.268	0.013	0	0.16	$X^1_{0,1}$	0.164	0.351	0.403	0.076	0.006
Risk of gas pipeline	0.116	0.299	0.416	0.153	0.016	0.38	$L_G(P)$	0.014	0.077	0.276	0.577	0.858
Risk of gas well	0.181	0.355	0.424	0.040	0	0.38	X	0.190				
Risk of gas compressor	0.100	0.381	0.513	0.006	0	0.08						

The subsystems of the OGSS can be ranked with respect to their contribution to FAR of the OGSS. Ranking of subsystems can be performed by measuring the decrease value in the FAR of OGSS, if risk value of a subsystem is considered as zero. Offshore gas pipeline has the highest contribution to FAR of system; therefore, it is ranked as the most important subsystem in the system. Offshore gas well, holder and compressor are ranked second, third and fourth respectively. The proposed methodology is capable of identifying the FAR of the system and rank the subsystems based on their contribution to FAR of system. With the help of FFTA (Chapter 5), risk analysts will know which MCs in the subsystems are the more critical. The results of this chapter and Chapter 5 help the analysts to select the best RCOs (Chapter 6) for mitigating risks of the subsystems and system respectively.

4.9.5 Risk updating

In the hierarchical structure described earlier, ER updating can be done at any level of the hierarchy when new evidence is available. In this step, the ER approach with its attached software Intelligent Design System (IDS) software is employed to combine evidence obtained from two or more sources. The risk updating is performed by recalculating of risk value with considering new evidence on $X_{1,1}^{3*}$. The existing risk value of $X_{1,1}^{3*}$ is $m_1(X_{1,1}^{3*}) = [0.06, 0.19, 0.36]$ (Table 4.8) with the weight factor of $w(m_1) = 0.52$. Assume new evidence is obtained from different expert with weight factor of $w(m_2) = 0.48$ and risk value of $m_2(X_{1,1}^{3*}) = [0,0,0.1,0.2]$. IDS is employed to merge the new data with the existence one. Figure 4.7 shows the result of merging of data.

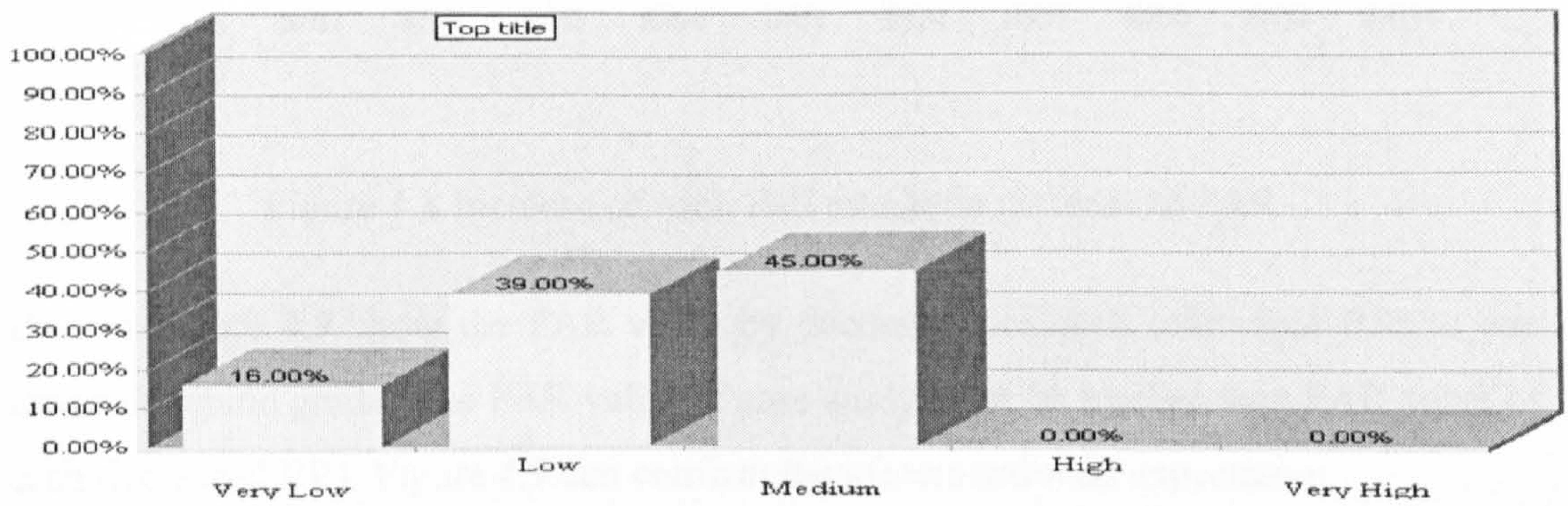


Figure 4.7 Result of merging new data with the existence one

The value of $X_{1,1}^{3*}$ is changed from $[0,0.34,0.66,0,0]$ to $m_{12}(X_{1,1}^{3*}) = [0.16,0.39,0.45,0,0]$. The process of risk calculation must be repeated to obtain a new FAR. The value of the new FAR is 0.16. The new result is obtained by considering the new evidence at risk item $X_{1,1}^{3*}$.

4.9.6 Validation results of fuzzy aggregative risk assessment method

Sensitivity analysis is performed to validate the proposed methodology. The model must satisfy the three axioms described in Section 4.8. The examination of the model reveals that when a basic risk item increases or decreases the FAR increases and decreases respectively. The first bar in the Figure 4.8 and Figure 4.9 show the FAR value of case study. Other bars in Figure 4.8 show the value of FAR by increasing of each individual basic risk item to one higher linguistic grade respectively. As mentioned, the FAR value of each increased basic risk item must be larger than the FAR value of case study. Figure 4.8 can satisfy the first expectation (Axiom 1).

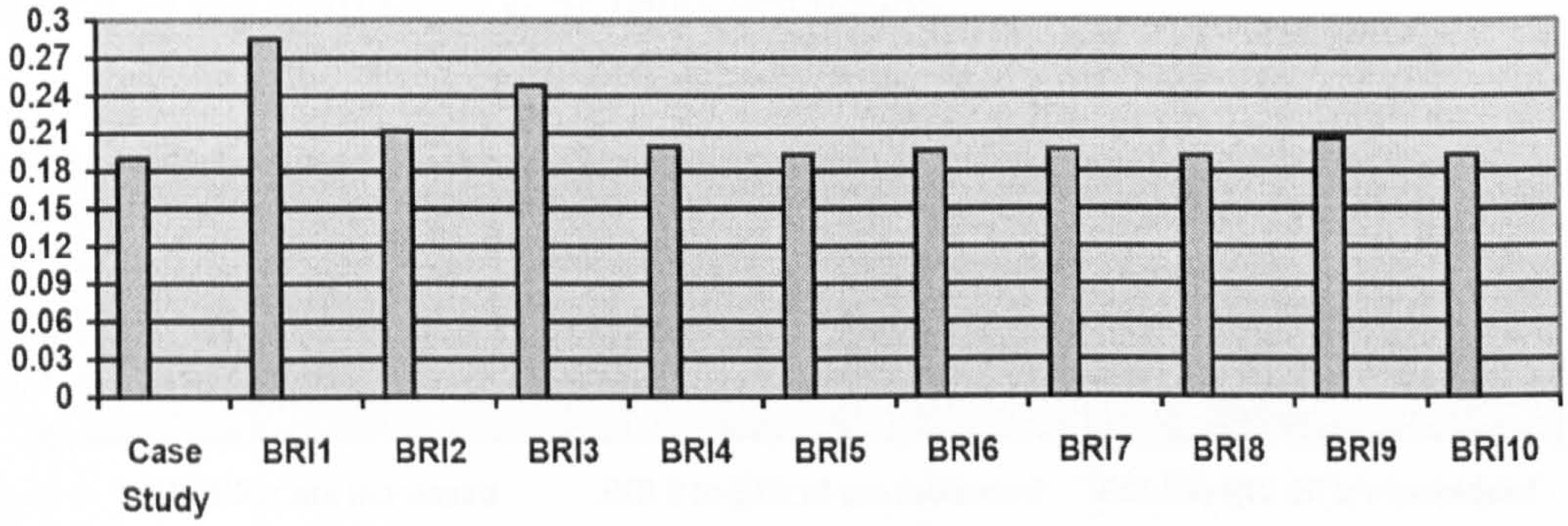


Figure 4.8 Increase of each BRI results in increase of FAR

Bars in Figure 4.9 show the FAR value by decreasing of each individual BRI to one lower linguistic grade. The FAR value of case study must be smaller than FAR value of each decreased BRI. Figure 4.9 can confirm the aforementioned expectation.

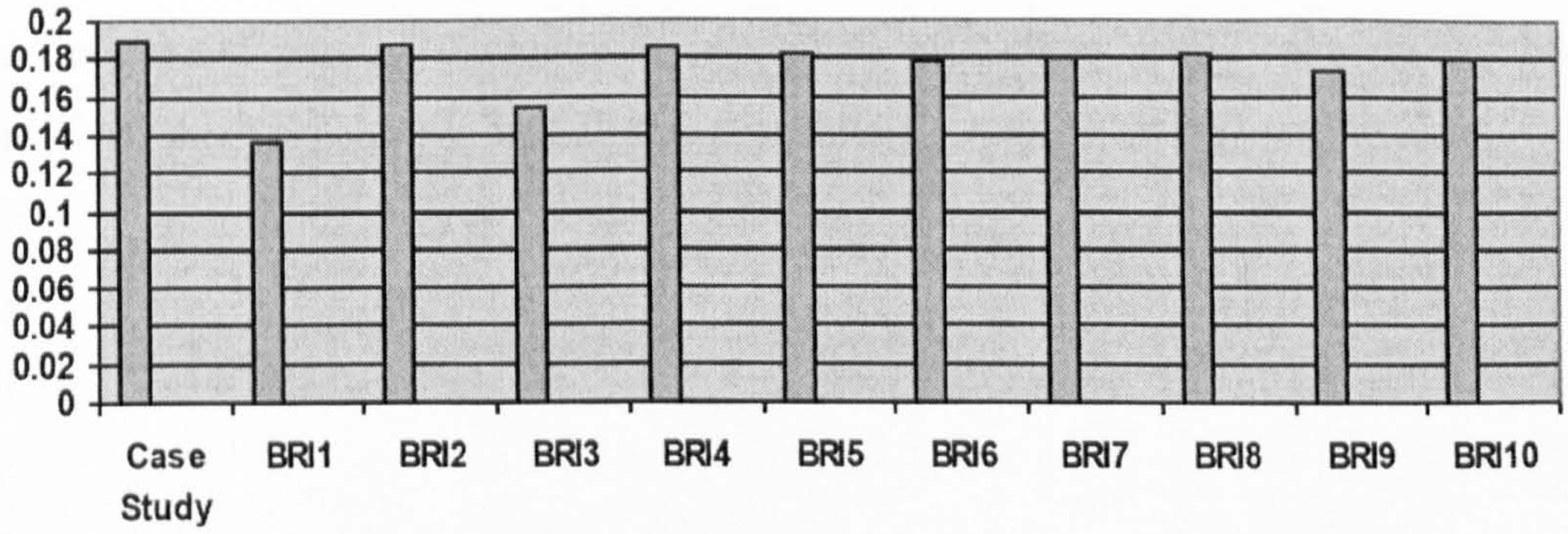


Figure 4.9 Decrease of each basic risk item results in decrease of FAR

As shown in Figure 4.10, the first bar presents the value of FAR by considering the increment of all basic risk items (basic risk item 1 to basic risk item 10) to one higher linguistic grade. The second and third bars show the value of FAR by increasing basic risk item 2 to basic risk item 10 and basic risk item 4 to basic risk item 10 to one higher linguistic grade respectively. The FAR value of increasing all basic risk items must be larger than the one of increasing a subset of such basic risk item s. Therefore, FAR values must be as follows:

FAR value of all basic risk items> FAR value of basic risk item 2 to basic risk item 10> FAR value of basic risk item 4 to basic risk item 10

Figure 4.10 can confirm the aforementioned results.

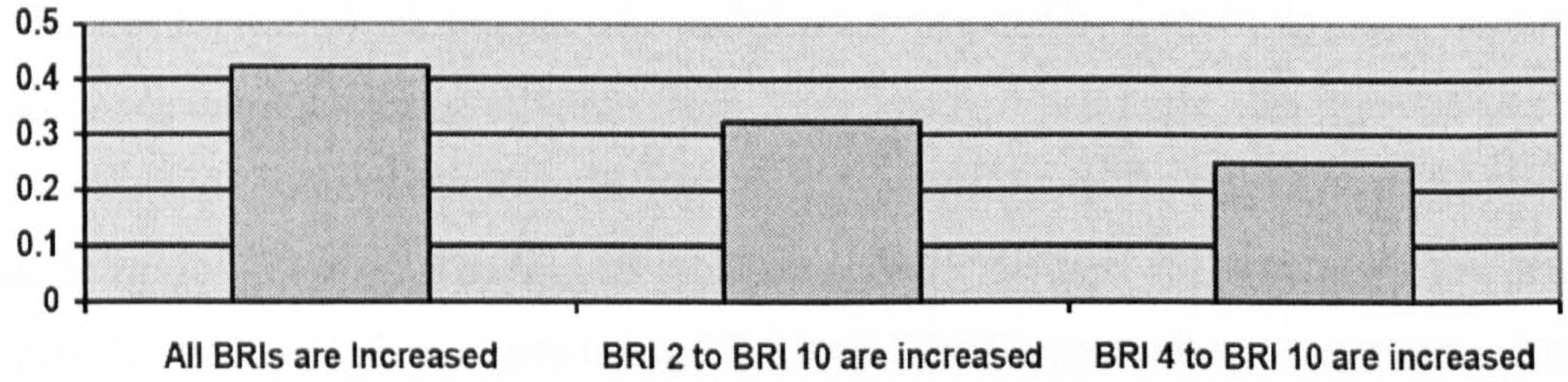


Figure 4.10 Comparison of increasing all the basic risk items and increasing its subsets

L and S of all the basic risk items are decreased to one lower level. Therefore, it is tested that the value of the resultant FAR with all such basic risk item s is smaller than the value of the resultant FAR with any subset of $(x-y)$ such basic risk items where $y \in x$. Figure 4.11 shows an example of comparing FRA values when all basic risk items and part of them are decreased to one lower grade. The results of the sensitivity analysis can confirm all the expectations in the three different axioms.

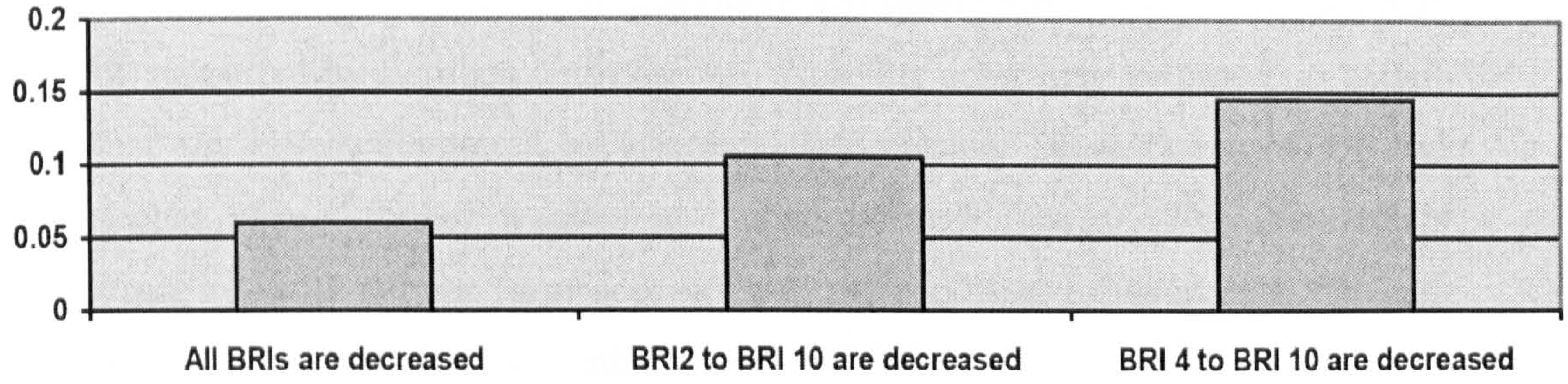


Figure 4.11 Comparison of decreasing all basic risk items and decreasing its subsets

4.10 Conclusion

A proposed model using FRA, FAHP and ER is presented in this chapter for determining the aggregative risk of various sources. The rate of risk is defined by the product of L and S. Risk factors of L and S are expressed by a multiple level, qualitative scaling scheme increasing in value from Very low to Very high. The qualitative scales are expressed by fuzzy numbers to capture the vagueness in the linguistic subjectivity of risk definition. During grouping of attributes, FAHP is used for estimating the priority matrix (weights). Risk analysis using FRA and FAHP approaches can estimate domain human experts experience and risk management knowledge. The advantages of the proposed methodology are:

- It enables the synthesis of both qualitative and quantitative information in a single framework.
- It can explicitly handle and propagate data with uncertainties, for which probability distributions are unknown.
- It has the ability to update estimates based on the newly arrived data.
- It is modular and scalable and new knowledge can be accommodated at any stage and in any form.
- It is easily programmable for a computer application and could be used as risk analysis tool for an OGSS.

The main limitation of the proposed method is:

- This framework supports both qualitative and quantitative data. Some data may be supported by rigorous observations, while the other may be based on beliefs that are loosely supported by anecdotal information. These two types of data should have different weights in the aggregation process. The hierarchical structure in its current form does not address this need to distinguish between data obtained from sources with different reliabilities.

In the model development stages, the FAR value is expected to have limited meaning for the acceptable level of risk to the general public. It is envisaged that as the proposed hierarchical structure is developed, risk items are populated and improved upon (using newly obtained data), the designers and analysts of an OGSS will gain insight into acceptable risk levels as they are manifested in the final risk values. This approach could serve as a basis for bench-marking acceptable risks in OGSSs.

Chapter 5

Fuzzy Fault Tree Analysis of OGSSs

Summary

Probabilistic Risk Assessment (PRA) is a comprehensive, structured and logical analysis method aimed at identifying hazards and assessing their risks of complex systems. FTA as a PRA method is used to identify basic causes leading to an undesired event, to represent logical relation of these basic causes in leading to the event, and finally to calculate the probability of occurrence of this event. To conduct a quantitative FTA, one needs a fault tree along with failure data of the Basic Events (BEs). Sometimes it is difficult to have an exact estimation of the failure rates of individual components or the probabilities of occurrence of undesired events due to a lack of sufficient data. Furthermore, due to imprecision in failure data of BEs, the overall result may be questionable. To avoid such conditions, a fuzzy approach may be used with the FTA technique. This reduces the ambiguity and imprecision arising from the subjectivity of data. The methodology is developed using a systematic approach of fault tree development, Minimal Cut Sets (MCSs) determination and probability analysis. This chapter also illustrates with a case study the use of importance measures in sensitivity analysis.

5.1 Introduction

FTA is a logical and diagrammatic method to evaluate the probability of top event that results from sequences of faults and failure events. The fault tree is useful for understanding the mode of occurrence of an accident in a logical way. Furthermore, given the failure probabilities of the BEs (i.e. system components), the occurrence probability of the TE can be calculated. This chapter considers the quantitative solution of the fault trees developed in Chapter 3 to quantitatively evaluate the cause-effect relationships in an OGSS (Figure 5.1). However, conventional probabilistic methods cannot be directly adopted in this study because the input data is not only represented in terms of probabilistic numbers but also fuzzy numbers. Therefore, FFTA is investigated in this section. Fuzzy numbers are used to represent the likelihood of occurrence of BEs which are at the bottom level of the fault tree. FFTA is performed to generate the quantitative results used to represent the likelihood of occurrence of the TE.

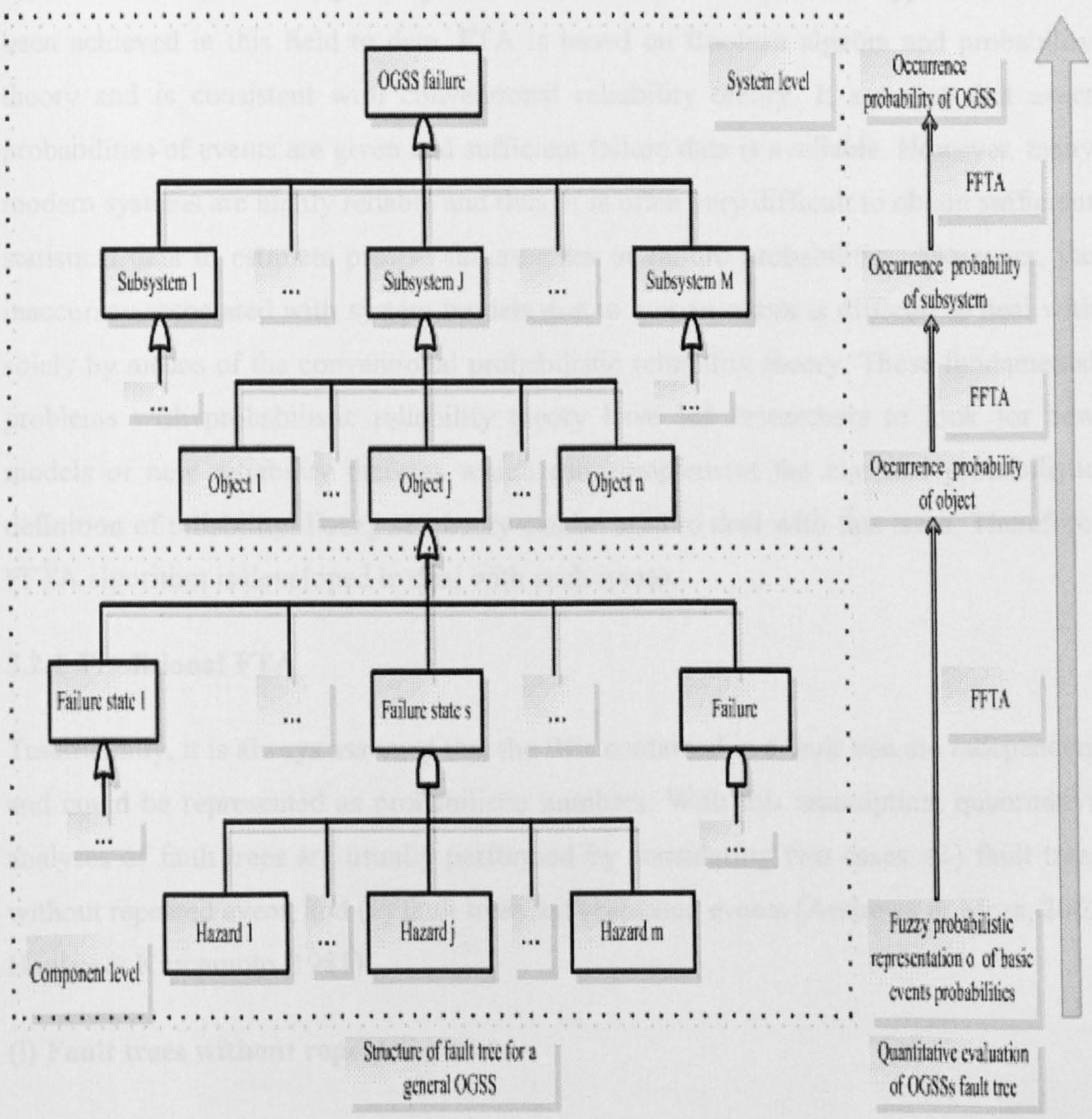


Figure 5.1 Quantitative method used to evaluate the fault trees of the OGSS

Besides the likelihood of the TE, another useful result of FTA is importance measures for BEs that identify contribution of the BEs to the occurrence of the TE. The importance measures are used for ranking the importance of different BEs. In this chapter, Section 5.2 introduces basic concepts of FFTA and reviews the methods used with FFTA. Section 5.3 describes the proposed methodology for this chapter. Section 5.4 presents a case study. Lastly, Section 5.5 gives the conclusion.

5.2 Basics of FFTA

FTA is a powerful and computationally efficient technique for analysing and predicting system reliability and safety. Many theoretical advances and practical applications have been achieved in this field to date. FTA is based on Boolean algebra and probability theory and is consistent with conventional reliability theory. It assumes that exact probabilities of events are given and sufficient failure data is available. However, many modern systems are highly reliable and thus, it is often very difficult to obtain sufficient statistical data to estimate precise failure rates or failure probabilities. Moreover, the inaccuracy associated with system models due to human errors is difficult to deal with solely by means of the conventional probabilistic reliability theory. These fundamental problems with probabilistic reliability theory have led researchers to look for new models or new reliability theories which can complement the classical probabilistic definition of reliability. Fuzzy set theory can be used to deal with this issue. Therefore, FFTA algorithm is developed to deal with such issues.

5.2.1 Traditional FTA

Traditionally, it is always assumed that the BEs contained in a fault tree are independent and could be represented as probabilistic numbers. With this assumption, quantitative analyses of fault trees are usually performed by considering two cases: (1) fault trees without repeated event, and (2) fault trees with repeated events (Andrews & Moss, 2002; Henley & Kumamoto, 1981).

(i) Fault trees without repeated events

If the fault tree for a TE contains independent BEs which appear only once in the tree structure, the TE probability can be obtained by working the BE probabilities up through the tree. In doing this, intermediate gate event ("and" or "or") probabilities are calculated by starting at the base of the tree and working upwards until the TE probability is obtained. Figure 5.2 demonstrates "and" and "or" intermediate gate events.

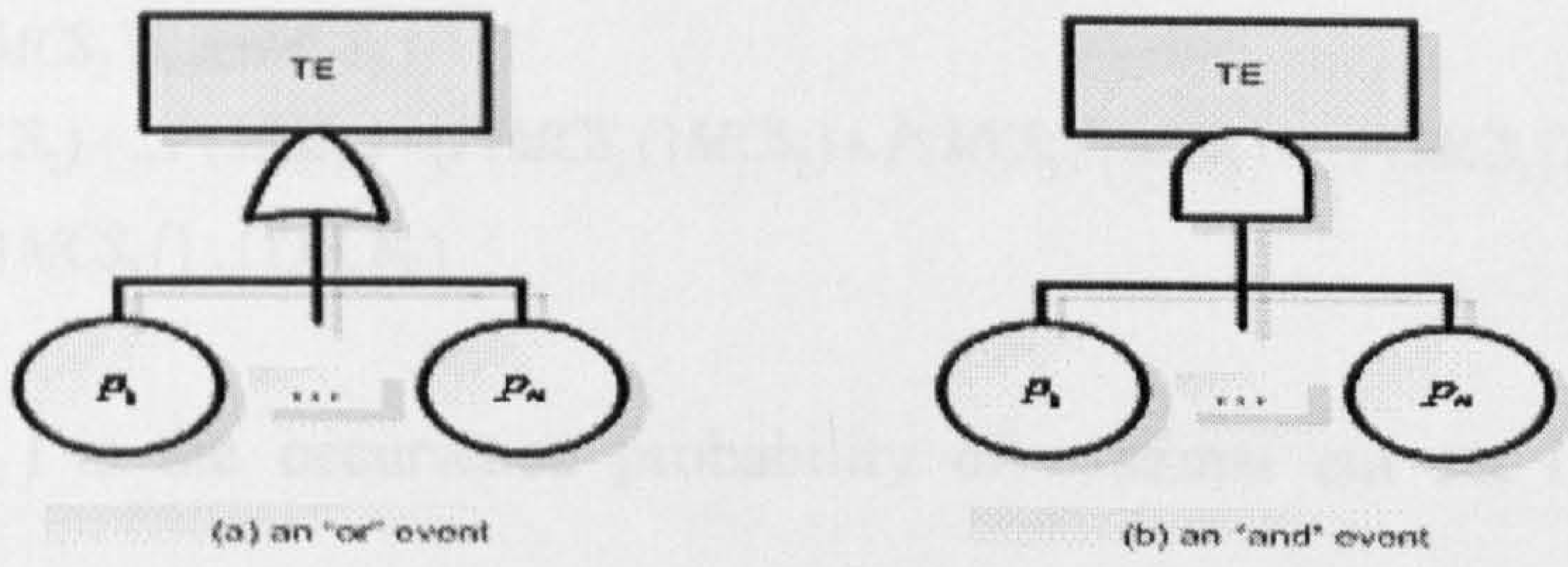


Figure 5.2 Symbol representation of "and" and "or" gates in fault trees

For an "and" gate event, its probability is obtained by Equation 5.1.

$$P = \prod_{i=1}^{n} p_i \tag{5.1}$$

where P is the probability of the TE; p_i denotes the occurrence probability of BE i; and n is the number of BEs associated with the "or" gate. For an "or" gate event, its probability is determined by Equation 5.2.

$$P = 1 - \prod_{i=1}^{n} (1 - p_i) \tag{5.2}$$

where P is the probability of TE; p_i denotes the occurrence probability of BE i; and n is the number of BEs associated with the "or" gate.

(ii) Fault trees with repeated events

When fault trees have BEs which appear more than once, the methods most often used to obtain the TE probability utilise the Minimal Cut sets (MCs). A MC is a collection of BEs. If all these events occur, the TE is guaranteed to occur; however, if any BE does not occur, the TE will not occur. Therefore, if a fault tree has n_c MCs (MC_i , $i = 1, \ldots, n_c$) then the TE "T" exists if at least one MCS exists (Andrews & Moss, 2002), i.e.

$$T = MCS_1 + MCS_2 + \ldots + MCS_N = \bigcup_{i=1}^{n_c} MCS_i \tag{5.3}$$

An exact evaluation of the TE occurrence likelihood can be obtained by Equation 5.4.

$$P(T) = P(MCS_1 \cup MCS_2 \cup ... \cup MCS_N)$$
$$= P(MCS_1) + P(MCS_2) + ..P(MCS_N) - (P(MCS_1 \cap MCS_2) + P(MCS_1 \cap MCS_3) + ..P(MCS_i \cap MCS_j)...)... \quad (5.4)$$
$$+ (-1)^{N-1} P(MCS_1 \cap MCS_2 \cap ... \cap MCS_N)$$

where $P(MCS_i)$ is the occurrence probability of minimal cut set i and N is the number of MCs..

5.2.2 Fuzzy FTA

In conventional FTA, the failure probabilities of system components are treated as exact values. However, for many systems, it is often very difficult to estimate the precise failure rates or probabilities of individual components or failure events in the quantitative analysis of fault trees from past occurrences. In other words the crisp approach has difficulty in conveying imprecision or vagueness nature in system modelling to represent the failure rate of a system component (Liang & Wang, 1993). This always happens under a dynamically changing environment or in systems where available data is incomplete or insufficient for statistical inferences. Therefore, in the absence of exact data, it may be necessary to work with approximate estimations of probabilities. Under these conditions, it may be inappropriate to use the conventional FTA for computing the system failure probability. Therefore, it is necessary to develop a novel formalism to capture the subjectivity and the imprecision of failure data for use in the FTA. Instead of the probability of a failure, it may be more appropriate to propose its possibility (Misra & Weber, 1990). The probability values of components will be characterized by fuzzy numbers.

With respect to this inadequacy of the conventional FTA, extensive research has been performed using fuzzy set theory in FTA. This pioneering research on this was conducted by Tanaka et al., (1983), which treated probabilities of BEs as trapezoidal fuzzy numbers, and applied the fuzzy extension principle to determine the probability of TE. Based on this work, further extensive researches were performed (Misra & Weber, 1990; Liang & Wang, 1993). Another variation of FFTA was given by Misra & Weber (1989). Their analysis was based on possibility distribution associated with the BEs and a fuzzy algebra for combining these events. Parallel with this, Singer (1990) analysed fuzzy reliability by using L-R type fuzzy numbers. In order to facilitate the calculation of Singer's method, Cheng & Mon (1993) and Chen (1994) proposed revised methods to analyse fault trees by specifically considering the failure FPs of BEs as triangular fuzzy numbers. In addition to the above studies, Onisawa (1988) proposed a method of using error possibility to analyse human reliability in a fault tree. By combining with Onisawa's work, Lin & Wang (1997) developed a hybrid method which can simultaneously deal with probability and possibility measures in a FTA. Sawer & Rao (1994) applied α-cuts to determine the failure probability of the TE in fuzzy fault trees of mechanical systems. Cai et al. (1991) and Huang et al. (2004) adopted possibility theory to analyse fuzzy fault trees. Dong & Yu (2005) applied the hybrid method to analyse failure probability of oil and gas transmission pipeline. Shu et al. (2006) used intuitionistic fuzzy methods to analyse fault trees on a printed circuit board assembly. Ping et al. (2007) presented a method which overcomes the drawbacks of traditional FTA by using FTA based on possibilistic measures and fuzzy logic. Pan & Wang (2007) used FFTA for assessing failures of bridge construction.

Extensive research has been carried out to determine the importance of BEs in FFTAs. Tanaka et al. (1983) defined an improvement index to evaluate the importance of each BE. Furuta & Shiraishi (1984) used representative values of fuzzy membership functions to calculate the importance. Liang & Wang (1993) used ranking values to evaluate fuzzy importance index. Suresh et al. (1996) applied Euclidean distance to determine fuzzy importance measures and fuzzy uncertainty importance measures, which was further improved by Guimarees & Ebecken (1999). It is obvious from the above reviews that FFTA has been extensively studied for a long time and effectively applied to many engineering problems. However, its application in OGSSs is still scarce and rarely reported. This research specifically investigates the application of FFTA in OGSSs.

5.3 Proposed model: FFTA of OGSSs

In circumstances where a lack or incompleteness of data exists, there is a need to incorporate expert judgements into risk research. A framework is proposed based on the fuzzy set theory with the FTA method is capable of quantifying the judgement from experts who express opinions qualitatively. The proposed framework is developed in eight different stages in Figure 5.3. In the first stage, the BEs with known failure rates are separated from those BEs with vague failure rates. The second stage is to obtain the failure probabilities of BEs with known failure rates. In the third stage, expert judgements are assigned to the BEs with vague failure rates. These ratings are generally in a fuzzy number form. The fourth stage is an aggregation procedure. It is performed by aggregating experts' opinions for BEs with vague failures through linguistic terms. A defuzzification process will then be adopted to transform the experts' judgements (fuzzy possibility) to the corresponding crisp possibility values by employing an appropriate algorithm. The sixth stage is to convert such crisp possibilities values to the failure probabilities. This is followed by estimating the MCSs and TE. In the last stage ranking of all the MCSs can consequently be produced. Figure 5.3 presents the structure of the proposed methodology.

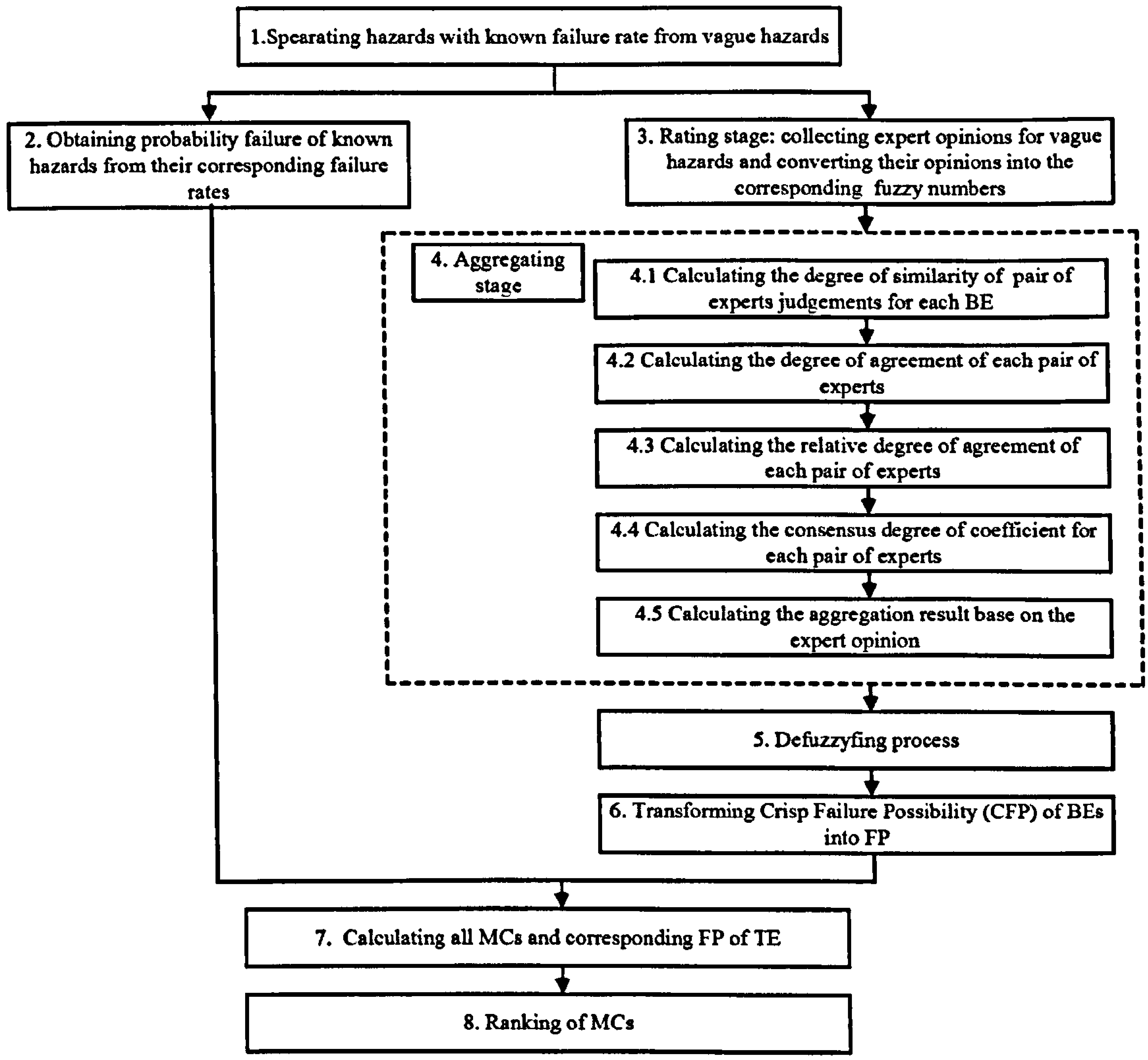


Figure 5.3 Structure of the proposed methodology

5.3.1 Separating hazards

As mentioned earlier, the first step of the methodology is a separation of hazards with known failure rate from vague hazards. Failure rates of some hazards are available from Offshore RElaibility DAta (OREDA, 2002). By using OREDA, it is possible to separate hazards with known failure rate from vague hazards associated with OGSSs.

5.3.2 Obtaining failure probability of hazards with known failure rate

The foundation of a good analysis is the pedigree of failure rate or event probability data that is assigned to BEs. A good faith effort must be made to obtain the best failure rate data that is available. The uncertainty in failure rate data depends in large part on the applicability of the data (its source). A failure rate should apply to the particular application of a component, its operating environment, and its non-operating environment. The failure rate data hierarchy is given as follows:

1. Actual mission data on the component.

2. Actual mission data on a component of similar design.

3. Life test or accelerated test data on the component.

4. Life test or accelerated test data on a similar component.

5. Field or test data from the component supplier.

6. Specialized data base or in-house data base on similar components.

7. Standard handbooks for reliability data such as OREDA.

There are predominantly three methods that could be used to determine the occurrence probability of an event namely (Preyssl, 1995):

1. Statistical method.

2. Extrapolation method.

3. Expert judgement method.

The statistical method uses the treatment of direct test of experience data and the calculation of probabilities. The extrapolation method involves the use of model prediction and similar condition or using standard reliability handbook. The expert judgement method uses direct estimation of probabilities by specialists.

A component is tested periodically with test interval τ . A failure may occur at any time in the test interval, but the failure is only detected in a test. After a test/repair, the component is assumed to be "as good as new". This is a typical situation for many safety-critical components, like sensors and safety valves. If an event failure is of a kind which can be inspected, the component failure probability can be obtained from Equation 5.5 (Spouge, 2000; Rausand & Hoyland, 2004).

$$P(t) = \frac{1}{2}\lambda\tau \tag{5.5}$$

where λ is the component failure rate and τ is the inspection interval.

If a component is of a kind which cannot be inspected. The component failure probability P, which is also called the unreliability, is determined from Equation 5.6.

$$P(t) = 1 - e^{-\lambda t} \tag{5.6}$$

where λ is the component failure rate and t is the relevant time interval. Based on the Maclaren Series, the above equation for P can be obtained from Equation 5.7 if $\lambda t << 1$

$$P(t) = 1 - (1 + \frac{-\lambda t}{1!} + \frac{\lambda^2 t^2}{2!} + \frac{-\lambda^3 t^3}{3!} + \cdots + \frac{\lambda^n t^n}{n!}) \cong \lambda t \tag{5.7}$$

5.3.3 Rating stage

During this stage, experts express their opinions for each BE with respect to each subjective attribute. Expert elicitation is the synthesis of experts' opinions of a subject where there is uncertainty due to insufficient data because of physical constraints or lack of resources (Rausand & Hoyland, 2004). Expert elicitation is essentially a scientific consensus methodology and is often used in the study of rare events. Expert elicitation allows for parameterization, an "educated guess", for the respective topic under study. Expert elicitation generally quantifies uncertainty.

The technique has been studied within many disciplines. Examples of fields that have contributed to probability elicitation are decision analysis, psychology, risk analysis, Bayesian statistics, mathematics and philosophy.

Quantification of subjective probabilities is employed in a number of circumstances (Korta et al., 1996 and SKB, 1999):

- Evidence is incomplete because it cannot be reasonably obtained.
- Data exists only from analogous situations (one might know the solubility of one mineral and might use this information to infer the solubility of another mineral).
- There are conflicting models or data sources.
- Scaling up from experiments to target physical processes is not direct (scaling of mean values is often much simpler than rescaling uncertainties).

Expert knowledge is influenced by individual perspectives and goals (Ford & Sterman, 1998). Therefore, complete impartiality of expert knowledge is often difficult to achieve. An important consideration in the selection of experts is whether to use a heterogeneous group of experts (e.g. both scientists and workers) or a homogenous group of experts (e.g. only scientists). The effect of difference in personal experience on expert judgement is assumed to be smaller in homogenous group compared to a heterogeneous group. A heterogeneous group of experts can have an advantage over a homogenous group through considering all possible opinions. In summary, criteria to identify experts are based on (1) a person's period of learning and experience in a specific domain of knowledge, thus influencing his or her judgmental and analytical behaviour, and (2) the specific circumstances in which experience is gained, e.g. in theoretical or practical circumstances.

In this study, a heterogeneous group of experts is selected for evaluating the probability of vague events. The weighting factors of experts are determined according to Table 5.1.

Table 5.1 Weighting scores of different experts

Constitution	Classification	Score
Professional Position (PP)	Senior academic	5
	Junior academic	4
	Engineer	3
	Technician	2
	Worker	1
Service Time (ST)	≥ 30 years	5
	20 - 29	4
	10 - 19	3
	6 - 9	2
	≤ 5	1
Education Level (EL)	PhD	5
	Master	4
	Bachelor	3
	HND	2
	School level	1

Rating of expert judgement can be carried out in linguistic terms, which are used for soliciting expert opinions for each basic event. The concept of linguistic term is very useful in dealing with situations, which are too ill defined or too complex to be described in conventional quantitative expression (Zadeh, 1965).

5.3.4 Aggregating stage

Since each expert may have a different opinion according to his/her experience and expertise in the relevant field, it is necessary to aggregate experts' opinions to reach a consensus.

Hsu & Chen (1994) presented an algorithm to aggregate the linguistic opinions of a homogeneous/heterogeneous group of experts. Suppose each expert, E_k $(k = 1,2,\ldots,M)$ expresses his/her opinion on a particular attribute against a specific context by a predefined set of linguistic variables. The linguistic terms can be converted into corresponding fuzzy numbers. The detailed algorithm is described as follows:

1. Calculate the degree of agreement (degree of similarity) $S_{uv}(\widetilde{R}_u, \widetilde{R}_v)$ of the opinions $\widetilde{R}_u$ and $\widetilde{R}_V$ of a pair of experts E_u and E_v, where $S_{uv}(\widetilde{R}_u, \widetilde{R}_v) \in [0,1]$. According to this approach, $\widetilde{A} = (a_1, a_2, a_3, a_4)$ and $\widetilde{B} = (b_1, b_2, b_3, b_4)$ are two standard trapezoidal fuzzy numbers. Then the degree of similarity between these two fuzzy numbers can be obtained by the similarity function of S, which is defined as:

$$S(\widetilde{A},\widetilde{B})=1-\frac{1}{4}\sum_{i=1}^{4}|a_i-b_i| \quad (5.8)$$

where $S(\widetilde{A},\widetilde{B})\in[0,1]$. The larger value of $S(\widetilde{A},\widetilde{B})$, the greater similarity between two fuzzy numbers of $\widetilde{A}$ and $\widetilde{B}$.

2. Calculate the Average Agreement (AA) degree $AA(E_u)$ of the experts.

$$AA(E_u)=\frac{1}{M-1}\sum_{\substack{u\neq v \\ v=1}}^{M} S(\widetilde{R}_u,\widetilde{R}_v) \quad (5.9)$$

3. Calculate the Relative Agreement (RA) degree, $RA(E_u)$ of the experts.

$$E_u(u=1,2,\ldots,M)\text{ as } RA(E_u)=\frac{AA(E_u)}{\sum_{u=1}^{M} AA(E_u)} \quad (5.10)$$

4. Estimate the Consensus Coefficient (CC) degree, $CC(E_u)$ of expert, $E_u(u=1,2,\ldots,M)$:

$$CC(E_u)=\beta\cdot w(E_u)+(1-\beta)\cdot RA(E_u). \quad (5.11)$$

where β $(0\leq\beta\leq1)$ is a relaxation factor of the proposed method. It shows the importance $w(E_u)$ over $RA(E_u)$. When $\beta=0$ no importance has been given to the weight of an expert and hence a homogeneous group of experts is used. When $\beta=1$, the consensus degree of an expert is the same as its importance weight. The consensus degree coefficient of each expert is a good measure for evaluating the relative worthiness of each expert's opinion. It is the responsibility of the decision maker to assign an appropriate value to β.

5. Finally, the aggregated result of the experts' judgments, $\widetilde{R}_{AG}$, can be obtained as follows:

$$\widetilde{R}_{AG}=CC(E_1)\times\widetilde{R}_1+CC(E_2)\times\widetilde{R}_2+\cdots+CC(E_M)\times\widetilde{R}_M \quad (5.12)$$

5.3.5 Defuzzification process

Defuzzification is the process of producing a quantifiable result in fuzzy logic. Defuzzification problems emerge from the application of fuzzy control to the industrial processes (Zhao & Govind, 1991). Fuzzy numbers defuzzification is an important procedure for decision making in fuzzy environment. The centre of area defuzzification technique is selected here. This technique was developed by Sugeno in 1985 (Sugeno, 1999). This is the most commonly used technique and is accurate. This method can be expressed as:

$$X^* = \frac{\int \mu_i(x)xdx}{\int \mu_i(x)} \quad (5.13)$$

where X^* is the defuzzified output, $\mu_i(x)$ is the aggregated membership function and x is the output variable. The above formula can be shown as follows for triangular and trapezoidal fuzzy numbers. Defuzzification of fuzzy number $\tilde{A} = (a_1, a_2, a_3)$ is:

$$X^* = \frac{\int_{a_1}^{a_2} \frac{x-a}{a_2-a_1} xdx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} xdx}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} dx + \int_{a_2}^{a_3} \frac{a_3-x}{a_3-a_2} dx} = \frac{1}{3}(a_1+a_2+a_3) \quad (5.14)$$

Defuzzification of trapezoidal fuzzy number $\tilde{A} = (a_1, a_2, a_3, a_4)$ can be obtained by Equation 5.15.

$$X^* = \frac{\int_{a_1}^{a_2} \frac{x-a}{a_2-a_1} xdx + \int_{a_2}^{a_3} xdx + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} xdx}{\int_{a_1}^{a_2} \frac{x-a_1}{a_2-a_1} dx + \int_{a_2}^{a_3} xdx + \int_{a_3}^{a_4} \frac{a_4-x}{a_4-a_3} dx} = \frac{1}{3} \frac{(a_4+a_3)^2 - a_4a_3 - (a_1+a_2)^2 + a_1a_2}{(a_4+a_3-a_2-a_1)} \quad (5.15)$$

5.3.6 Transforming Crisp Failure Possibility (CFP) of BEs into failure probability

As aforementioned, there are data available for failure rates of some events whilst the data associated with the others are vague. There is inconsistency between failure probabilities of certain hazards and CFPs of vague events. This issue can be solved by transforming CFPs of vague events into the form of failure probabilities. This transformation can be performed by using Equation 5.16. Onsiawa (1998) has proposed a function which can be used for converting CFP to failure probability. This function is derived by addressing some properties such as the proportionality of human sensation to the logarithmic value of a physical quantity. The probability rate can be obtained from possibility rate as follows (Onsiawa, 1998; Onsiawa and Nishiwaki, 1998; Onsiawa, 1988; Onsiawa, 1990; Onsiawa, 1996; Lin and Wang, 1998):

$$FP = \begin{cases} \frac{1}{10^K}, CFP \neq 0 \\ 0, CFP = 0 \end{cases} \quad , \quad K = \left[\left(\frac{1-CFP}{CFP} \right) \right]^{\frac{1}{3}} \times 2.301 \tag{5.16}$$

5.3.7 Calculating all MCSs and occurrence of TE

By definition, an MCS is a combination (intersection) of BEs leading to the TE. The combination is a "minimal" combination in that all the failures are needed for the TE to occur; if one of the failures in the MCS does not occur, then the TE will not occur (by this combination). Any fault tree will consist of a finite number of MCs that are unique for that TE. One-component MCSs, if there are any, represent those single failures that will cause the TE to occur. Two-component MCSs represent the double failures that together will cause the TE to occur. TE can be obtained from MCSs by using Equation 5.4.

5.3.8 Ranking of MCs

One of the most important outputs of an FTA is the set of importance measures that are calculated for the TE. Such importance measures establish the significance for all the MCSs in the fault tree in terms of their contributions to the TE probability. Both intermediate events (gate events) as well as MCSs can be prioritized according to their importance. Importance measures can also be calculated that give the sensitivity of the top event probability to an increase or decrease in the probability of any event in the fault tree. Two types of TE importance measure can be calculated for the different types of applications. The importance measures that can be calculated for each MCS in the fault tree are described as follows:

Fussell-Vesely Importance Measure (F-VIM) is the contribution of the MCS to the TE probability. F-VI measures are determinable for every MCS modelled in the fault tree. This provides a numerical significance of all the fault tree elements and allows them to be prioritized. The F-VI is calculated by summing all the causes (MCSs) of the TE involving the particular event. This measure has been applied to MCSs to determine the importance of individual MCS. Where $Q_i(t)$ is the contribution of MCS i to failure of the system, the importance measure can be quantified as follows (Modarres, 2006):

$$I_i^{FV}(t) = \frac{Q_i(t)}{Q_S(t)} \tag{5.17}$$

$Q_i(t)$ = Probability of failure of MC i

$Q_S(t)$ = Probability of failure of TE due to all MCs

Risk Reduction Worth (RRW) measures the decrease in the probability of the TE if a given MCS is assured not to occur. This importance measure can also be called the Top Decrease Sensitivity (TDS). RRW for a MCS shows the decrease in the probability of the TE that would be obtained if the MCS did not occur. Therefore, the RRW can be calculated by re-quantifying the fault tree with the probability of the given MCS to 0. It thus measures the maximum reduction in the TE probability. An RRW value is determinable for every MCS in the fault tree.

5.4 Case study

The proposed methodology is applied to one of the OGSS subsystems in this section. The offshore gas pipeline fault tree is selected as the case study.

5.4.1 Separating hazards with known failure rate from hazards with unknown failure rate

The elements of the fault tree logic diagram are divided into hazards with known occurrence probabilities and hazards with unknown occurrence probabilities. 17 hazards are identified for pipeline gas leakage. 10 of them are hazards with known occurrence probabilities whilst there are not historical data available for the other 7 hazards. The probabilities 7 of such hazards can be obtained by applying subjective linguistic evaluation. Table 5.2 presents all the hazards associated with the constructed fault tree.

Table 5.2 Gas pipeline hazard probabilities

Gas pipeline hazard	Fault tree Ref.	Hazard failure rate	Gas pipeline hazard	Fault tree Ref.	Hazard failure rate
1.Bad installation	H_{111}	Linguistic term	10.Maintenace	H_{141}	Linguistic term
2.Bad weld	H_{112}	Failure rate	11.Human error	H_{142}	Linguistic term
3.Unsutiable material	H_{121}	Failure rate	12.Earth quake	H_{21}	Failure rate
4.Inadequate strength	H_{122}	Failure rate	13.Turbidty current	H_{22}	Failure rate
5.Acid	H_{1311}	Failure rate	14.Mud flow	H_{23}	Linguistic term
6.High water ratio	H_{1312}	Failure rate	15.Dropped object	H_{311}	Linguistic term
7.Tensile stress	H_{1313}	Failure rate	16.Trawling	H_{312}	Linguistic term
8.Internal corrosion	H_{132}	Failure rate	17. Terrorist activity	H_{32}	Linguistic term
9.External corrosion	H_{133}	Failure rate			

5.4.2 Calculating FPs of hazards with known failure rate

As previously mentioned, the foundation of a good analysis is the pedigree of failure rate or event occurrence probability data that is assigned to BEs. Therefore, occurrence probabilities of hazards with known failure rate can be estimated by using Equations 5.5 to 5.7. For example, the failure rate of internal corrosion is $1\times10^{-3}\dfrac{1}{km.year}$ with 4 inspections in a year. Therefore, FP of internal corrosion can be obtained by using Equation 5.5 as follows:

$$FP_{Internal\ corrosion}=\frac{1}{2}\times1\times10^{-3}\times\frac{4}{12}=6.6\times10^{-4}\frac{1}{km.year}$$

The failure probabilities of the BEs with known failure rate are calculated and presented in Table 5.3.

Table 5.3 Failure probabilities of BEs

BEs	FP of BEs of known failure rate	BEs	FP of BEs of known failure rate
H_{112}	0.0004	H_{1313}	0.001
H_{121}	0.003	H_{132}	0.00066
H_{122}	0.0006	H_{133}	0.00035
H_{1311}	0.005	H_{21}	0.005
H_{1312}	0.002	H_{22}	0.001

5.4.3 Rating stage

In the proposed method, a numerical approximation system proposed by Chen and Hwang (1992) is used to convert linguistic terms to their corresponding fuzzy numbers. There are generic verbal terms in the system where scale 1 contains two verbal terms (linguistic terms) and scale 8 contains 13 verbal terms (linguistic terms). The typical estimate of human working memory capacity is seven plus-minus two chunks, which means that the suitable number for linguistic term selection for human beings to make an appropriate judgement is between 5 and 9 (Miler, 1956; Nicokis and Tsuda, 1985). Therefore, conversion scale of 6 which contains 5 verbal terms is selected for performing the subjective assessment of hazards with unknown failure rate. Figure 5.4 introduces the fuzzy linguistic scale that is used in this chapter to determine the judgements of experts with respect to hazards with unknown failure rate.

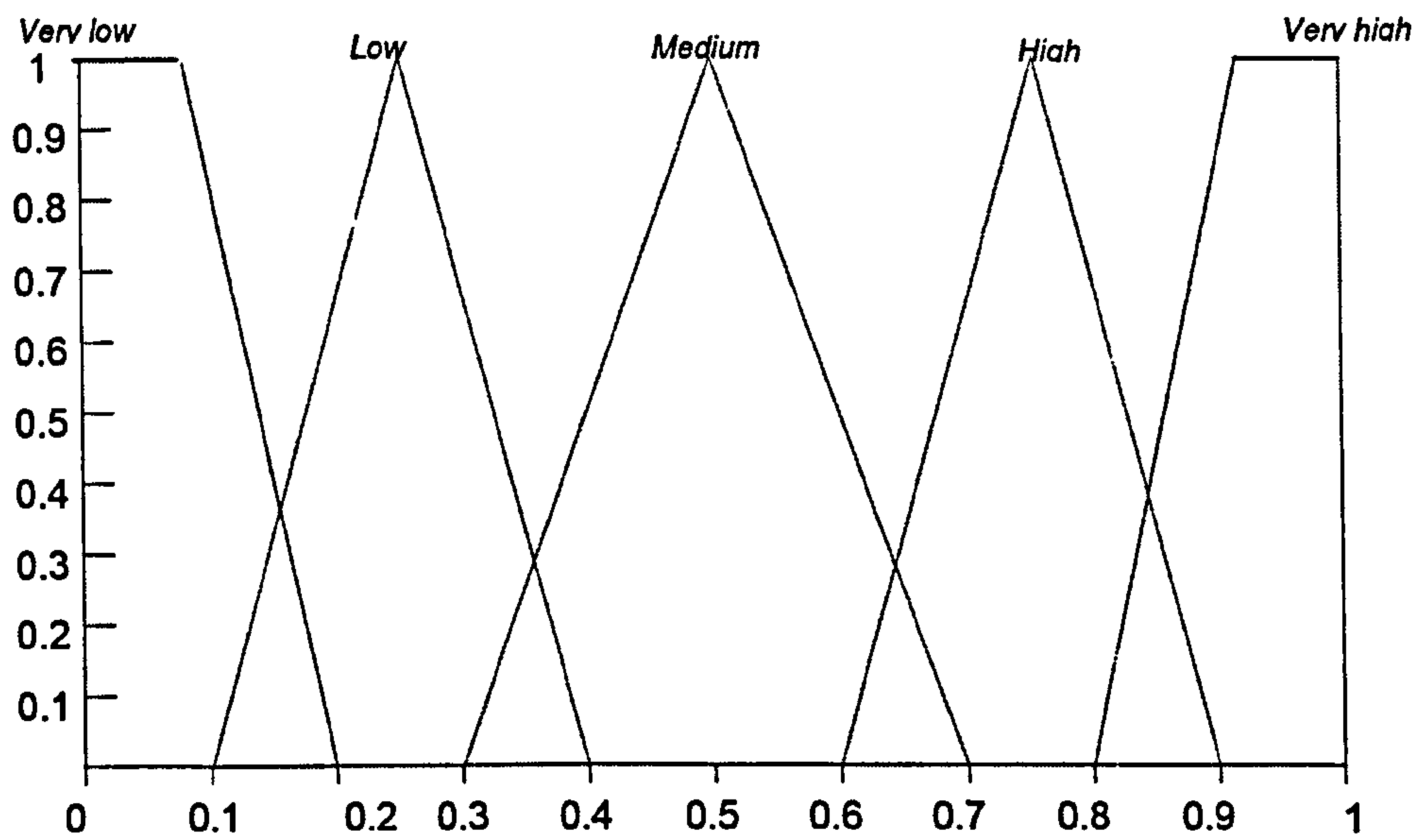


Figure 5.4 Chen and Hwang conversion scale 7

The linguistic terms of Figure 5.4 are in the form of both triangular and trapezoidal fuzzy numbers. All of the triangular fuzzy numbers can be converted into the corresponding trapezoidal fuzzy numbers for the ease of analysis. Table 5.4 presents all the fuzzy numbers of Figure 5.4 in the form of trapezoidal fuzzy numbers.

Table 5.4 Fuzzy number of conversion scale 6

Linguistic terms	Fuzzy sets
Very Low (VL)	(0,0,0.1,0.2)
Low	(0.1,0.25,0.25,0.4)
Medium	(0.3,0.5,0.5,0.7)
High	(0.6,0.75,0.75,0.9)
Very High (VH)	(0.8,0.9,1,1)

As previously mentioned, a heterogeneous group of experts is employed to perform the judgement for the vague events. The weights of the experts are not equal. The experts' weights can be obtained by using Table 5.1. Three experts are employed for performing the judgements. Table 5.5 shows the experts' weights. This table is particularly tailored for this research project.

Table 5.5 Experts weight

No of expert	Title	Service time (Year)	Education level	Weighting factor	Weighting score
1	Senior academic	10-19	PhD	5+3+5=13	0.38
2	Engineer	20-29	Master	3+4+4=11	0.32
3	Engineer	20-29	Bachelor	4+3+3=10	0.30
				Total: 34	Total: 1

Expert judgements on the BEs with unknown failure rate are illustrated in Table 5.6.

Table 5.6 Expert judgments on vague BEs

BEs	Expert judgment on vague BEs		
	E_1	E_2	E_3
H_{111}	M	M	L
H_{141}	L	L	VL
H_{142}	M	M	L
H_{23}	M	H	H
H_{311}	H	H	H
H_{312}	VL	L	L
H_{32}	L	M	VL

5.4.4 Aggregation for obtaining estimates of BEs

In this stage, all the ratings are aggregated under each subjective BE. As an example, the detailed aggregation calculations for BE of "H_{111}" are given in Table 5.7. β is considered as 0.5 in the aggregation calculation of the subjective BEs.

Table 5.7 Aggregation calculations for the BE of "H_{111}"

Expert 1 (E1)	0.3	0.5	0.5	0.7
Expert 2 (E2)	0.3	0.5	0.5	0.7
Expert 3 (E3)	0.1	0.25	0.25	0.4
S (E1&2)	1	AA (E1)	0.875	
S (E1&3)	0.75	AA (E2)	0.875	
S (E2&3)	0.75	AA (E3)	0.75	
RA (E1)	0.35	CC (E1)	0.365	
RA (E2)	0.35	CC (E2)	0.335	
RA (E3)	0.3	CC (E3)	0.3	
Weight of expert 1 (E 1)	0.38			
Weight of expert 2 (E 2)	0.32			
Weight of expert 3 (E 3)	0.3			
Aggregation for H_{111}	0.24	0.425	0.425	0.61

These calculations contain attribute based aggregation calculations, such as Average degree of Agreement (AA), Relative degree of Agreement of each expert (RA), etc. After the aggregation calculations, the results of all the BEs are presented in Table 5.8.

Table 5.8 Aggregation calculations for each subjective BE

BEs	Aggregation of each subjective BE
H_{111}	(0.24,0.425,0.425,0.61)
H_{141}	(0.07,0.17,0.2,0.34)
H_{142}	(0.24,0.425,0.425,0.61)
H_{23}	(0.5,0.665,0.665,0.832)
H_{311}	(0.6,0.75,0.75,0.9)
H_{312}	(0.06,0.163,0.198,0.33)
H_{32}	(0.13,0.25,0.28,0.43)

5.4.5 Defuzzification process of subjective BEs

The centre of area defuzzification technique is employed to calculate the defuzzification of all the subjective BEs. Table 5.9 shows the result of subjective BEs defuzzification.

Table 5.9 Defuzzification results for all subjective BEs

BEs	Aggregation of subjective basic events	Defuzzification of subjective BEs (CFP)
H_{111}	(0.24,0.425,0.425,0.61)	0.425
H_{141}	(0.07,0.17,0.2,0.34)	0.197
H_{142}	(0.24,0.425,0.425,0.61)	0.425
H_{23}	(0.5,0.665,0.665,0.832)	0.665
H_{311}	(0.6,0.75,0.75,0.9)	0.75
H_{312}	(0.06,0.163,0.198,0.33)	0.189
H_{32}	(0.13,0.25,0.28,0.43)	0.274

5.4.6 Converting CFPs of BEs into failure probability

The CFPs of the subjective BEs can be transformed into the corresponding failure probabilities by using Equation 5.16. Table 5.10 presents the failure probabilities of all the subjective BEs.

Table 5.10 Converting CFP into failure probability

BEs	FP of subjective BEs
H_{111}	0.002
H_{141}	0.0002
H_{142}	0.002
H_{23}	0.014
H_{311}	0.025
H_{312}	0.0001
H_{32}	0.0006

5.4.7 Calculating failure probability of TE

To quantify the occurrence probability of the TE of the fault tree, the occurrence probability for each BE in the fault tree must be provided. These BE probabilities are then propagated upward to the TE using the Boolean relationships. The BE probabilities can be propagated upward using MCSs. Table 5.11 presents the FPs of all the MCSs.

Furthermore, the occurrence probability of TE is obtained by using Equation 5.4. The occurrence probability of the TE is $0.0538\frac{1}{km.year}$.

Table 5.11 Failure probability of all MCs

MCSs	Occurrence probability	MCSs	Occurrence probability	MCSs	Occurrence probability
1. H_{111}	0.002	6. H_{132}	0.00066	11. H_{22}	0.001
2. H_{112}	0.0004	7. H_{133}	0.00035	12. H_{23}	0.014
3. H_{121}	0.003	8. H_{141}	0.0002	13. H_{311}	0.025
4. H_{122}	0.0006	9. H_{142}	0.002	14. H_{312}	0.0001
5. (H_{1311} H_{1312} H_{1313})	0.00000001	10. H_{21}	0.005	15. H_{32}	0.0006

5.4.8 Ranking of Minimal Cut Sets (MCSs)

An important objective of many reliability and risk analyses is to identify those components or MCSs that are the most important (critical) from a reliability or risk viewpoint so that they can be given priority with respect to improvements. Table 5.12 presents the ranking of MCSs based on their calculated importance levels.

Table 5.12 Importance level of each MCS

No of MCs	Occurrence probability of MCs	F-VIM	Ranking of MCs
MCs1	0.002	0.036	5
MCs2	0.0004	0.007	11
MCs3	0.003	0.054	4
MCs4	0.0006	0.010	9
MCs5	0.00000001	1.8E-07	15
MCs6	0.00066	0.027	7
MCs7	0.00035	0.006	12
MCs8	0.0002	0.003	13
MCs9	0.002	0.036	5
MCs10	0.005	0.091	3
MCs11	0.001	0.018	8
MCs12	0.014	0.256	2
MCs13	0.025	0.457	1
MCs14	0.0001	0.001	14
MCs15	0.0006	0.010	9

In a *sensitivity analysis*, an input data parameter, such as a component failure probability is changed, and the resulting change in the TE probability is determined.

This is repeated for a set of changes using either different values for the same parameter or changing different parameters, e.g., changing different failure probabilities. Usually for a given sensitivity evaluation, only one parameter is changed at a time. This is called a one-at-a-time sensitivity study. This method is employed here to validate the sensitivity of the proposed model. RRW is employed to perform sensitivity analysis. The RRW can be calculated by setting an MCSs probability to 0. It is expected that elimination of the MC that has the highest contribution to the occurrence of TE should result in reducing the occurrence rate of TE more than other MCSs. Therefore, ranking of RRW values is expected to be the same as the ranking result of MCSs in Table 5.12. As shown in Table 5.13, MCS13 has the highest contribution to the TE occurrence probability. Therefore, the RRW value of MCS13 must be the largest. As demonstrated in Table 5.13, the RRW value of MCS13 is 0.0248 which is the highest as expected. Table 5.13 shows the ranking result which remains the same as the one in Table 5.12. The proposed model satisfies the aforementioned expectations.

Table 5.13 Result of sensitivity analysis

	TE=0.0538					
No of MCSs	Occurrence probability of MCs	F-VI M	MCs rank	New TE	RRW=TE-New TE	RRW rank
MCSs1	0.002	0.036	5	0.0519	0.0019	5
MCSs2	0.0004	0.007	11	0.0534	0.0004	11
MCSs3	0.003	0.054	4	0.0509	0.0029	4
MCSs4	0.0006	0.010	9	0.0532	0.0006	9
MCSs5	0.00000001	1.8E-07	15	0.0537	0.00001	15
MCSs6	0.00066	0.027	7	0.0530	0.0008	7
MCSs7	0.00035	0.006	12	0.0535	0.0003	12
MCSs8	0.0002	0.003	13	0.0536	0.0002	13
MCSs9	0.002	0.036	5	0.0519	0.0019	5
MCSs10	0.005	0.091	3	0.0490	0.0048	3
MCSs11	0.001	0.018	8	0.0531	0.0007	8
MCSs12	0.014	0.256	2	0.0404	0.0134	2
MCSs13	0.025	0.457	1	0.0290	0.0248	1
MCSs14	0.0001	0.001	14	0.0537	0.0001	14
MCSs15	0.0006	0.010	9	0.0532	0.0006	9

5.5 Conclusion

In this chapter a structured framework has been developed that may help the analyst to identify the critical MCSs in the system. From the result of this study, the following conclusions are drawn:

- A fuzzy methodology for fault tree evaluation seems to be a viable alternative solution to overcome the weak points of the conventional approach: insufficient information concerning the occurrences frequencies of hazardous events.

- By using linguistic variables, it is possible to handle the ambiguities involved in the expression of the occurrence of a hazard (BE). In addition, the state of each hazard can be described in a more flexible form using the concept of fuzzy set.

- Instead of using the CFP, failure probability is used to characterize the failure occurrence of the system events. It can efficiently express the vagueness nature of system phenomena and insufficient information.

- The importance measure can provide useful information for improving the safety performance of a system. F-VI measure index assists the analyst in identifying the critical MCSs in the system for reducing occurrence likelihood of a TE.

However there is another point that needs to be considered for further studies:

- The basic events are considered as independent in this study. In the future research, it is required to develop a method for taking into account dependency between hazards.

Chapter 6

Application of MADM in a Fuzzy Environment for Selecting the Best RCO in OGSSs

Summary

A Fuzzy MADM (FMADM) method, which is suitable for treating group decision making problems in a fuzzy environment, is proposed for ranking RCOs from a cost-benefit view point. It is obvious that much knowledge in the real world is fuzzy rather than precise. In OGSSs ranking problems, MADM decision data is usually fuzzy, crisp, or a combination of the two. A useful model is proposed here in order to handle both fuzzy and crisp data. Imprecision and ambiguity in the calculation of a performance rating are incorporated into MADM whereby fuzzy set theory provides a mathematical framework for modelling them. Human opinions often conflict in group decision-making. The purpose of fuzzy MADM is to aggregate the conflicting opinions. In general, each expert's opinion for a given attribute may be different from others'. Therefore, it is necessary to develop an appropriate method of aggregating multiple experts' opinions, taking into account a degree of importance of each expert in the aggregation procedure. The weights of all attributes and experts are estimated using a FAHP. Finally, the best RCO with respect to cost and benefit is selected using a TOPSIS method.

6.1 Introduction

MADM is a common task in human activities. It consists of finding the preferred alternative from a given set of alternatives. The increasing complexity of the socio-economic environment makes it less likely that a single decision maker can consider all the relevant aspects of a problem (Kim & Ahn, 1999; Kim et al., 1999; Xu, 2000). In such situations, the preference information provided by the decision maker may be imprecise or incomplete. As a result, many decision making processes in the real world take place in group settings with incomplete information. There have been a few studies employing imprecise preference models in group settings to date (Anandaligam, 1989; Chen, 2000; Herrera et al., 2005; Lahdelma, 2005). Anandaligam (1989) developed a methodology to use multiple attribute utility functions within a bargaining model. Salo (1995) developed an interactive method to aggregate the preferences of group members in the context of an evolving value representation. Kim & Ahn (1997) suggested the possibility that individually optimized results can be used to build group consensus, and considered strict or weak dominance values as inputs for aggregation procedures.

Park & Kim (1997) proposed a dominance graph and also presented an algorithm to generate the dominance graph based on the information of pair-wise dominance. Kim et al. (1999) presented an interactive procedure for multiple attribute group decision making with incomplete information and described some theoretical models to establish a group's pairwise dominance relations using utility ranges with a separable linear programming technique. Kim & Ahn (1999) suggested a procedure to rank alternatives by comparing the net strengths of alternatives. Chen (2000) extended the TOPSIS of Hwang and Yoon (1981) to a fuzzy environment and developed a vertex procedure to calculate the distance between two triangular fuzzy numbers. The same paper defined a closeness coefficient to determine the ranking order of all alternatives by simultaneously calculating the distances to both the fuzzy positive-ideal solution and fuzzy negative-ideal solution.

Li & Yang (2004) extended the classical linear programming technique for multidimensional analysis of preference (LINMAP) to develop a new methodology to solve multiple attribute group decision making problems in a fuzzy environment. They constructed a fuzzy linear programming model to rank alternatives by using the pairwise comparisons between alternatives, which can be used in both crisp and fuzzy environments. Lahdelma et al. (2005) developed a Ref-SMAA method to solve problems where both attribute data and preference information are uncertain or inaccurate (or preference information is absent). Olcer & Odabasi (2005) introduced an attribute based aggregation technique to deal with fuzzy multiple attribute group decision making problems. Herrera et al. (2005) presented an aggregation procedure to manage non-homogeneous information of a different nature (numerical and linguistic).

However, in many real-life cases, such as negotiation processes or in high technology projects etc, a decision maker cannot generally specify exact attribute weights but can only provide value ranges (Li & Yang, 2004; Parkan, 1994; Park & Kim, 1997; Park, 2004). The information about attribute values usually takes the form of linguistic variables or triangular fuzzy numbers (Chen, 2000; Li & Yang, 2004). This is due to:

- Decisions being made under time constraint and lack of knowledge or data (Park et al, 1996; Weber, 1987; Xu, 2000; Yang & Xu, 2002).
- Attributes being intangible or non-monetary because they reflect social and environmental impacts (Kim et al., 1999).
- Decision makers having limited attention and information processing capabilities (Kahneman et al., 1982).
- Group settings with which all participants do not have equal expertise about problem domain (Ramanathan & Ganesh, 1994).

Furthermore, during the decision making process a decision maker often needs to interact with group members (or analysts) by providing and modifying their incomplete preference information gradually. All of the above methods are somewhat unsuitable for dealing with these situations; therefore, it is necessary to pay attention to the aforementioned issues. In this chapter, an interactive method for multiple attribute group decision making under a fuzzy environment is developed where the information about attribute weights is partially known, the weights of decision makers and attribute values are expressed as trapezoidal fuzzy numbers.

6.2 Background

6.2.1 MADM

Decision making with more than one criterion to be considered occurs frequently in our daily living. Though these Multiple Criteria Decision Making (MCDM) problems are diverse, they share some mutual characteristics (Hwang & Yoon, 1981).

Conflict can exist among the criteria – Taking designing of a laptop as a simple example, the objective of low production cost may sacrifice part of its performance.

Criteria are of incommensurable units – Each criterion has its own unit of measurement. In the same example, cost is indicated by dollars, battery life is measured by minutes while processor speed is expressed by gigahertz (GHz).

Either design or selection is the target – The goal of MCDM is either to design the optimal alternative or to choose the best one from the predefined alternatives.

The last characteristic actually offers a way to classify MCDM problems, which can be broadly classified in two categories: Multiple Objective Decision Making (MODM), and Multiple Attribute Decision Making (MADM). Table 6.1 describes and compares the features of the two classes.

Table 6.1 Characteristics of MODM and MADM

	MODM	MADM
Criteria defined	Objective	Attribute
Goal	Explicit	Implicit
Constraint	Active	Inactive
Alternative	Infinite field	Finite field
Decision space	Continuous	Discrete
Usage	Design	Selection/Evaluation

The decision matrix in a MADM method contains four main parts, namely: (a) alternatives, (b) attributes, (c) weights, and (d) measures of performance of alternatives with respect to the attributes. The basic information involved in a MADM model can be expressed by the following matrix:

$$\begin{array}{c} \\ D = \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_k \end{array} \end{array} \begin{array}{c} \begin{array}{cccc} AT_1 & AT_2 & \cdots & AT_n \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{k1} & x_{k2} & \cdots & x_{kn} \end{bmatrix} \end{array} \tag{6.1}$$

$$W = \begin{bmatrix} w_1 & w_2 & \cdots & w_n \end{bmatrix}$$

where $A_1, A_2, \ldots, A_k$ are alternatives from which decision makers choose; AT_1, AT_2, ..., AT_n are attributes with which each alternative performance is measured; each x_{ij}, $i = 1,\ldots,k$, $j = 1,\ldots,n$ is the rating of alternative A_i with respective to attribute AT_j, and w_j is the weight of attribute AT_j. Some important issues with respect to MADM are explained as follows:

A) *Quantification of qualitative ratings*. An alternative in a MADM problem is often described by qualitative attributes. When no attribute data is available, the preferred approach is to assign numerical values to qualitative data scaling (linguistic terms). A fuzzy set approach is a viable method for dealing with this issue.

B) *Normalization of attribute ratings*. Attribute ratings are usually normalised to eliminate computational problems caused by different measurement units in a decision matrix. The normalization procedure attempts to obtain comparable scales, allowing attribute comparisons. There are two popular normalisation methods in the MADM methods:

(1) Linear normalization, this procedure divides the ratings of a certain attribute by its maximum value. The normalsied value of x_{ij} can be obtained by Equation 6.2.

$$r_{ij} = {x_{ij}}/{x_j^*} \quad i = 1,\ldots,k; j = 1,\ldots,n \tag{6.2}$$

where x_j^* is the maximum value x_{ij} . r_{ij} values vary between 0 to 1 $(0 \le r_{ij} \le 1)$.

(2) Vector normalization, this method divides the ratings of each attribute by its norm, so that each normalsied rating of x_{ij} can be obtained by Equation 6.3.

$$r_{ij} = {x_{ij}}\Big/{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \quad i = 1,\ldots,k; j = 1,\ldots,n \tag{6.3}$$

6.2.2 Fuzzy TOPSIS

Yoon and Hwang (1981) developed the TOPSIS method based upon the concept that a chosen alternative should have the shortest distance from the Positive Ideal Solution (PIS) and the farthest distance from the Negative Ideal Solution (NIS). This method ranks alternatives according to their distances from the ideal and the negative ideal solutions. The ideal solution is identified with a hypothetical alternative that has the best values for all considered attributes, whereas the negative ideal solution is identified with a hypothetical alternative that has the worst attribute values. The TOPSIS method has some positive characteristics compared with other MADM methods. Firstly, performance is only slightly affected by the number of alternatives. Secondly, rank discrepancies are amplified to a lesser extent when increasing the number of alternatives and the number of attributes.

In practice, TOPSIS has been successfully applied in solving selection/evaluation problems with a finite number of alternatives (Jee & Kang, 2000; Teodorovic, 1985; Yong, 2006). Furthermore, TOPSIS is based on solid logical foundation that reflects the rationale of human choice (Shiha et al., 2007). It has been proved to be one of the best methods in addressing the issue of rank reversal (Zanakis et al., 1998). However, RCO selection is often not crisply defined due to lack of data (Zimmermann & Zysno, 1985), therefore, many researchers have proposed fuzzy extensions of the TOPSIS method in order to eliminate the vagueness that is inherent in the corresponding evaluation problems (Chen, 2001; Yong, 2006; Li, 2007).

The aggregating function of the TOPSIS method does not yield results such that the highly ranked alternative is simultaneously the closest to the PIS and the furthest from the NIS since these criteria can be conflicting (Li, 2007). This issue is dealt with by the original TOPSIS method via the use of the notion of "relative closeness" which is a measure of the relative distance between a certain alternative and the PIS and NIS.

A new methodology for defining the aggregating function based on a fuzzy set representation of the distance to the PIS and NIS is proposed. This new methodology suggests the aggregating function to be modelled as the membership function of the intersection of two fuzzy sets, i.e. the fuzzy set of an alternative that has "the shortest distance from the ideal solution" and the fuzzy set of the alternative that has "the farthest distance from the negative ideal solution". In particular, the use of the class of intersection connectives of fuzzy sets that is developed by Yager (1980) is a feature of the new methodology. Yager's class of connectives permits modelling of the relative importance of membership values as well as the "strength" of the intersection connective. Thus, it provides the mathematical basis for modelling the notion of closeness to the PIS and the NIS and enables a formal definition for the relationship between the proximity of the PIS and the NIS.

6.3 RCOs of a Gas Well in Operational Phase

A well barrier is defined by NORSOK D-010 (2004) as "an envelope of one or several dependent barrier elements preventing fluids or gases from flowing unintentionally from the formation into another formation or to surface". Well barrier can be viewed as a pressurized vessel (envelope) capable of containing the reservoir fluids. The two barrier principle is prevalent in Norway and in most oil and gas producing countries (NORSOK D-010, 2004). This principle means that there should be at least two well barriers in a well. A well can therefore be considered as a system of two or more pressurized vessels (envelopes) that prevent the fluid from entering the surroundings.

Figure 6.1 illustrates the well barrier system as pressure vessels. In Figure 6.1, the well tubular and the Christmas tree (X-mas tree) body constitute the vessel walls while the Surface Controlled Subsurface Safety Valve (SCSSV) and X-mas tree valves are illustrated as the outlet valves from the vessel. The innermost vessel illustrates the well barrier closest to the reservoir while the outer vessels illustrate the consecutive well barriers.

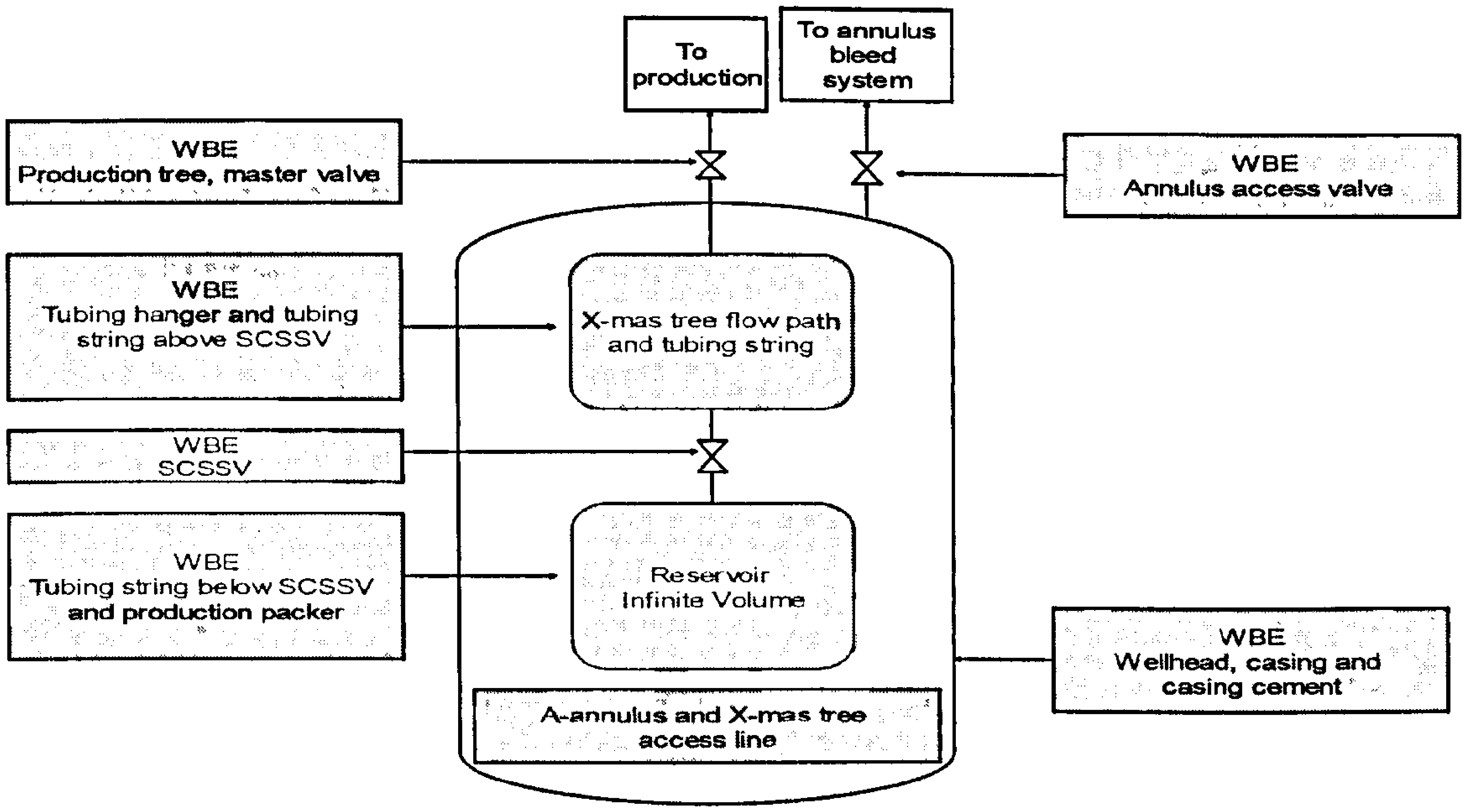


Figure 6.1 Illustration of well barriers to achieve integrity

A well barrier system should prevent uncontrolled outflow from the borehole/well into the external environment (NORSOK D-010). A well barrier is dependent on one or several Well Barrier Elements (WBEs) to fulfill its function. A failure of one WBE results in a failure of the well barrier. A system that is functioning if and only if all of its components are functioning is called a series structure. According to NORSOK D-010 there must be "at least two well barriers available during all well activities and operations, including suspended or abandoned wells, where a pressure differential exists that may cause uncontrolled outflow from the borehole/well to the external environment". This two barrier principle is well established throughout the oil industry. The well barrier closest to the reservoir is often called the primary well barrier, while the secondary well barrier prevents flow from the source. A system that is functioning if at least one of its components is functioning is called a parallel structure. Therefore, a system with a primary and secondary well barrier is a parallel structure (i.e., a redundant system). Redundancy is used to obtain high system availability. The well barrier system is functioning, if there is a connection either through the secondary or the primary well barrier, or both. The principle of two independent barriers is also important in terms of the system robustness. For example, if the wellhead on a production well is severely damaged the only remaining barrier against a severe blowout is the primary well barrier, namely the SCSSV and the tubing components below the SCSSV.

Center for Chemical Process Safety (CCPS) distinguishes between passive and active Independent Protection Layers (IPL) (CCPS, 2001). A *passive* protection layer is a protection layer that is not required to take action to achieve its function in reducing risk. An active protection layer is required to move from one state to another in response to a change in a measurable process property (e.g., temperature or pressure), or a signal from another source (such as a push-button or a switch). A well barrier can be viewed as a protection layer whose objective is to prevent flow from the reservoir. A well barrier will however be a combination of passive and active protection layer "elements". The protection layer categorization in CCPS (2001) is used in this thesis to distinguish between passive and active WBEs. Typical passive WBEs are the production packer, the seal assemblies and the tubing string. Active WBEs are the Production Master Valve (PMV), the Production Wing Valve (PWV), and the SCSSV. For these valves a signal has to be sent (input) to close the valve (state change). Each WBE has different functions and different performance criteria. Examples of the relation between WBE functions, failure modes, and acceptable deviations are given in Table 6.2. The table illustrates that active WBEs change state and therefore the acceptable deviation for the state transition must be defined in addition to the acceptable deviation in the passive state (leak rate in a closed position).

Table 6.2 WBE function and corresponding failures

WBE Type	Function	Failure mode	Acceptable deviation
1. Passive	Contain fluid, i.e. prevent leak across WBE	Leak across WBE	Leak rate (kg/s)
2.Active	Close WBE	Fail to close WBE	Closure time (S)
	Prevent leak (in closed position)	WBE leak in a close position	Leak rate (kg/s)

Petroleum Safety Authority (PSA) (2002) identifies three attributes that describe the performance of safety barriers in general:

1. *Functionality/efficiency*: the ability to function as specified in the design requirements.

2. *Reliability/availability*: the ability to function on demand or continuously.

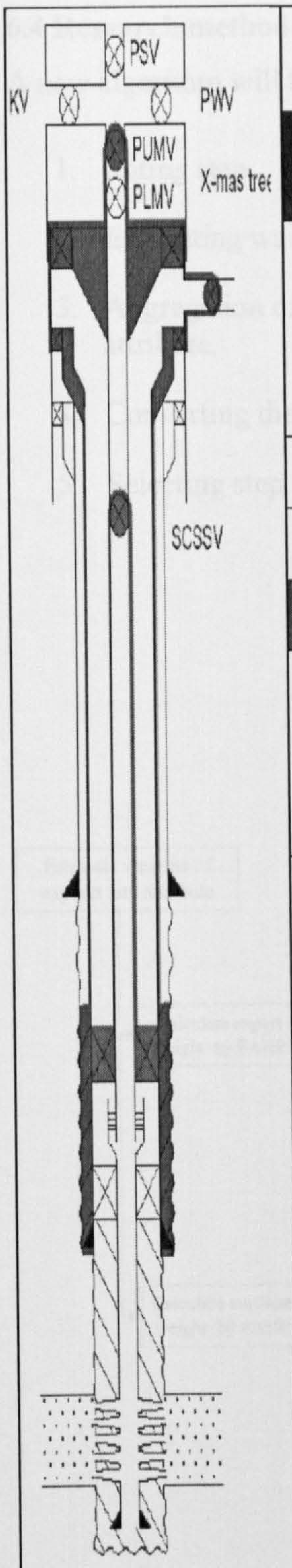
3. *Robustness*: the ability to function as specified under given accident conditions.

Robustness is included as the ability to function given external threats, while *availability* underlines the importance of the well barrier system to "function over time". *Functionality* is seen as part of the design process where all interfaces are considered. A list of generic well barrier requirements is given in NORSOK D-010. The requirements are grouped into the different system interface categories and explained in Appendix 5.

Different well barrier schematics in the drilling and operational phase are defined by NORSOK D-010. Figure 6.2 illustrates well barriers for well shut-in function in the operational phase. For performing the well shut-in function, the PMV is regarded as the outlet from the secondary well barrier, while the SCSSV is the outlet from the primary barrier (production/injection well). If the failed WBE is not part of these two envelopes, the failure does not influence the ability to shut-in the well on demand, and the well shut-in function complies with the two barrier principle. The two barrier principle also applies to well integrity, i.e., there should be two well barriers to prevent a blowout in normal operation. Two or more WBEs should therefore be intact in all leak paths. In addition to the two well barrier requirements, it is assumed that the primary barrier must always be intact. The primary barrier must be intact to allow for isolation of the well in the event of an external event damaging the wellhead. Four different RCOs with consideration of primary and secondary well barriers for well shut-in function during the operational phase are defined in order to prevent well leakage and blow-out. These RCOs are detailed in Table 6.3. The aim of this work is to select the best RCO with respect to cost and benefit.

Table 6.3 Description of each RCO

RCO1	Replacement of primary well barrier
RCO2	Repairing of primary well barrier
RCO3	Replacement of secondary well barrier
RCO4	Repairing of secondary well barrier



WBEs	Function
Primary well barrier	
1. Production packer	Provide a seal between the completion string and the casing/liner, to prevent connection from the formation into the A-annulus above the production packer.
2. SCSSV	Prevent flow of the hydrocarbons or fluid up the tubing.
3. Completion string	Provide a conduit for formation fluid from the reservoir to surface or vice versa.
Secondary well barrier	
1. Casing cement	Provide a continuous, permanent and impermeable hydraulic seal along hole in the casing annulus or between casing strings, to prevent flow of formation fluids, resist pressures from above or below, and support casing or liner strings structurally.
2. Casing	Provide a physical hindrance to uncontrolled flow of formation fluid or injected fluid between the bore and the back-side of the casing.
3. Tubing hanger	Support the weight of the tubing, prevent flow from the bore and to the annulus and provide a seal in annulus space between itself and the wellhead.
4. Well head	Provide mechanical support for the casing and tubing strings and for hook-up of risers or production tree and to prevent flow from the bore and annuli to formation or the environment.
5. Production tree	Provide a flow conduit for hydrocarbons from the tubing into the surface lines with the ability to stop the flow by closing the flow valve and/or the master valve.
6. Annulus and valve access line	Provide ability to monitor pressure and flow to annulus below the tubing hanger.

Figure 6.2 Well barriers for well shut-in function in its operational phase

6.4 Research methodology

A new algorithm will be developed in the following five major steps:

1. Rating step.
2. Estimating weights of experts and attributes.
3. Aggregation of expert judgments for obtaining the estimate of each subjective attribute.
4. Converting the aggregation result of subjective attributes to a crisp value.
5. Selecting step.

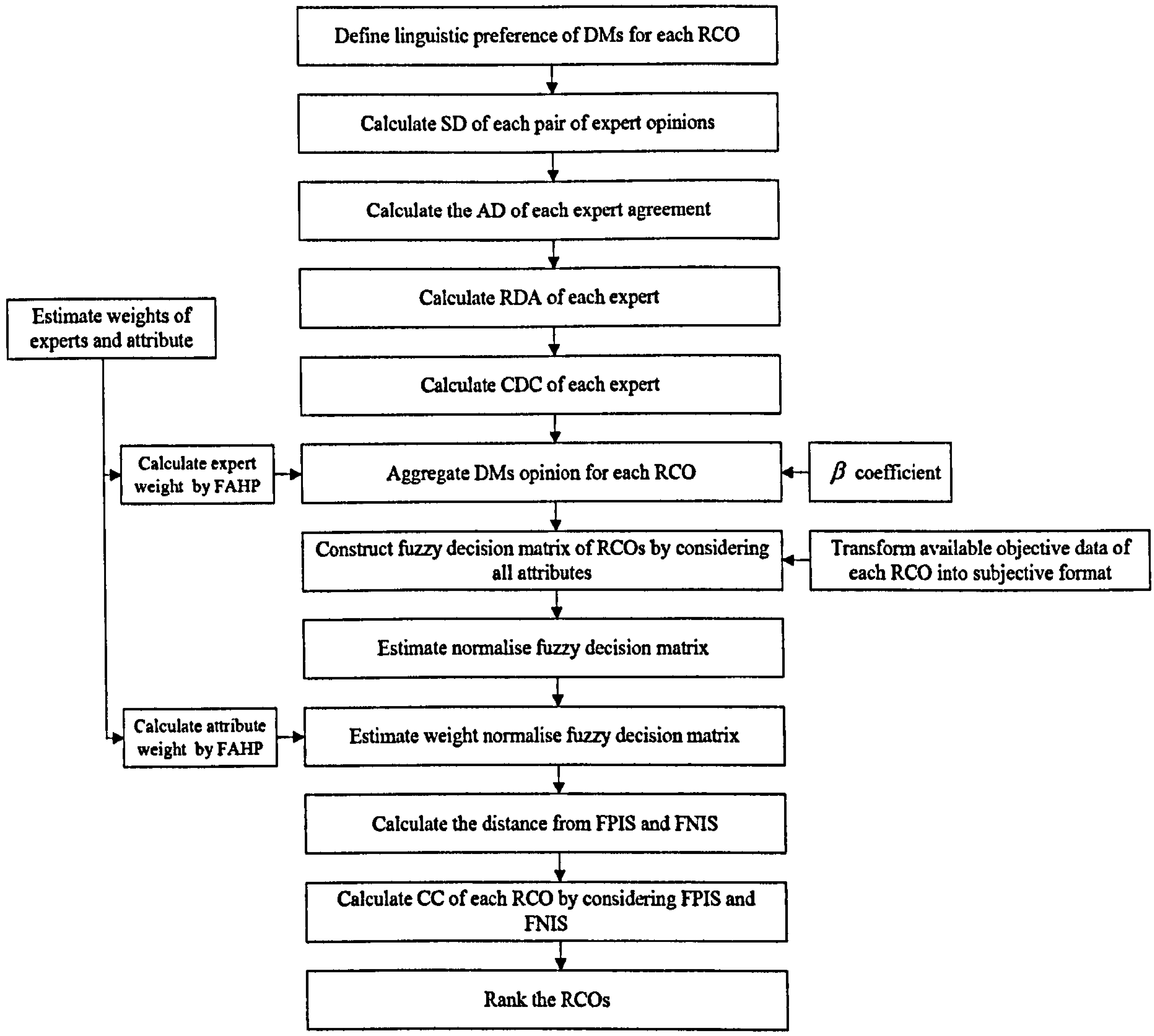


Figure 6.3 Structure of the proposed methodology

In the first step, the attributes are divided into subjective and objective groups. Each expert expresses his/her opinion about the identified subjective attributes. The expert opinions are in a form of linguistic terms or verbal statements. This kind of subjective judgment can be modelled by a fuzzy number.

In the second step the weights of attributes are obtained using FAHP. Experts' weights are estimated by employing the Delphi method. Then, an attribute based aggregation method for grouping experts' judgements is employed. One may conclude that the various experts are not equally important. This is known as a heterogeneous group of experts' problem. Aggregation is necessary only for the subjective attributes. After assigning a weight for each expert, all ratings are aggregated for each subjective attribute.

In the fourth step, all aggregated fuzzy numbers are converted into numeric rating using the centre of gravity method. The result of the last phase is a decision matrix, which contains fuzzy data. Subsequently the alternatives in hand are ranked by FTOPSIS. The conceptual model of the proposed method is illustrated in Figure 6.3.

6.4.1 Rating stage

In order to establish the decision matrix, experts express their opinions for each alternative with respect to each attribute. This can be done by soliciting expert opinions for each alternative by considering a subjective attribute. An expert's opinion can be in a form of linguistic terms such as low, medium or high. The concept of linguistic variables is very useful in dealing with situations which are too complex or too ill defined to be reasonably described by a conventional quantitative expression (Zadeh, 1965). The weights of various attributes and the ratings of each alternative with respect to each attribute are considered as linguistic variables. These linguistic variables are expressed in Table 5.4 (Chen & Hwang, 1992) and Table 4.6 (An et al., 2007).

6.4.2 Estimating weights of attributes and experts

6.4.2.1 Estimating weights of attributes

Consider m experts in a decision making process. Each element in a fuzzy pair-wise comparison can be calculated as follows:

$$\tilde{a}_{i,j} = \left(\frac{1}{m}\right) \otimes \left(e_{i,j}^{1} \oplus e_{i,j}^{2} \oplus \cdots e_{i,j}^{l} \cdots \oplus e_{i,j}^{m}\right) \tag{6.4}$$

$$\tilde{a}_{j,i} = \frac{1}{\tilde{a}_{i,j}} \tag{6.5}$$

where $\tilde{a}_{i,j}$ is the relative importance by comparing attribute i with attribute j by m experts, and $e_{i,j}^{l}$ is the lth expert's judgment on the comparison of attribute i with attribute j in a fuzzy number format. A $n \times n$ fuzzy pair-wise comparison matrix $\tilde{A}$ can be obtained as follows:

$$\tilde{A} = \begin{pmatrix} \tilde{a}_{1,1} & \tilde{a}_{1,2} & \cdots & \tilde{a}_{1,n} \\ \tilde{a}_{2,1} & \tilde{a}_{2,2} & \cdots & \tilde{a}_{2,n} \\ \vdots & \vdots & \tilde{a}_{i,j} & \vdots \\ \tilde{a}_{n,1} & \tilde{a}_{n,2} & \cdots & \tilde{a}_{n,n} \end{pmatrix} \tag{6.6}$$

Weight factors can be calculated using the geometric mean technique (Saaty, 1990; Tang et al., 2000; Mikhailov, 2004). $(\tilde{a}_{i,1}^{l}, \tilde{a}_{i,1}^{m}, \tilde{a}_{i,1}^{u})$ presents the lower bound (l), median (m) and upper bound (u) values of $\tilde{a}_{i,1}$.

$$\tilde{f}_i = \left(\tilde{a}_{i,1} \otimes \tilde{a}_{i,2} \otimes \cdots \tilde{a}_{i,j} \cdots \otimes \tilde{a}_{i,n}\right)^{\frac{1}{n}} = \left(\left(\tilde{a}_{i,1}^{l} \times \tilde{a}_{i,2}^{l} \times \cdots \times \tilde{a}_{i,n}^{l}\right)^{\frac{1}{n}}, \left(\tilde{a}_{i,1}^{m} \times \tilde{a}_{i,2}^{m} \times \ldots \times \tilde{a}_{i,n}^{m}\right)^{\frac{1}{n}}, \left(\tilde{a}_{i,1}^{u} \times \tilde{a}_{i,2}^{u} \times \cdots \times \tilde{a}_{i,n}^{u}\right)^{\frac{1}{n}}\right) \tag{6.7}$$

$$\tilde{w}_i = \frac{\tilde{f}_i}{\tilde{f}_1 \oplus \tilde{f}_2 \oplus \cdots \tilde{f}_i \cdots \oplus \tilde{f}_n} = (\sigma, \beta, \delta) \tag{6.8}$$

where $\tilde{f}_i$ is the geometric mean of the ith row in the fuzzy pair-wise comparison matrix and $\tilde{w}_i$ is the fuzzy weight factor of the ith attribute. As the outputs of the geometric mean method are triangular fuzzy weight factors, defuzzification is applied in order to convert triangular fuzzy weight factors into the corresponding crisp weight factors. A defuzzification approach used in FAHP is described below (Mikhailov, 2004):

$$DF\tilde{w}_i = \frac{1}{3}(\sigma + \beta + \delta) \tag{6.9}$$

where $DF\widetilde{w}_i$ is the defuzzified mean value of a fuzzy weight factor. The normalized weight of attribute i (w_i) can then be calculated by using Equation 6.10.

$$w_i = \frac{DF\widetilde{w}_i}{\sum_{i=1}^{n} DF\widetilde{w}_i} \tag{6.10}$$

6.4.2.2 Estimating weights of experts

The weighting of experts is determined according to Table 5.1. If an expert is considered "better" than others, then he/she is given a greater weight.

Experts' weights are obtained by estimating weight scores and weight factors of experts. Weight scores and weight factors of experts can be obtained by using Equations 6.11 and 6.12 respectively.

Weight score of expert i = Score of PP of expert i+Score of ST of expert i+Score of EL of expert i (6.11)

Weight factor of expert i = (Weight score of expert i)/ ($\sum_{i=1}^{n}$ Weight score of expert i)

(6.12)

6.4.3 Aggregating stage

Since each expert may have a different opinion according to his/her experience and expertise in the relevant field, it is necessary to aggregate experts' opinions to reach a consensus. Hsu & Chen (1994) presented an algorithm to aggregate the linguistic opinions of homogenous and heterogeneous groups of experts, which is presented in Chapter 5. The same algorithm is employed for aggregating experts judgements in this chapter.

6.4.4 Defuzzifying stage

Up to this stage, experts' opinions have been aggregated for each alternative under each subjective attribute. In order to rank the alternatives of the problem, all the aggregated fuzzy numbers must be defuzzified. Therefore, all the components of the decision matrix are crisp numbers and any classical method can be used at the selection stage. Each subjective element of matrix $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}, d_{ij})$ can be converted to its corresponding crisp value by using Equation 5.15.

6.4.5 Selection stage

In the selection stage, classical MADM methods can be utilised to determine the ranking order of alternatives. Consider k possible alternatives $A_1, A_2, \ldots, A_k$ from which m decision makers $p_m = (1,2,\ldots,m)$ have to choose the most desirable one on the basis of n attributes $AT_1, \ldots, AT_n$. In order to make an appropriate decision, the following steps are performed.

Step 1: *Construct the normalised fuzzy decision matrix.* Suppose the aggregation rate of alternative $A_i (i = 1,2,\ldots,k)$ for attribute $AT_j (j = 1,2,\ldots,n)$ is f_{ij} . Therefore, TOPSIS can be expressed in a matrix as follows:

$$D = (f_{ij})_{m\times n} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_k \end{array} \begin{array}{c} \begin{array}{cccc} AT_1 & AT_2 & \cdots & AT_n \end{array} \\ \begin{bmatrix} f_{11} & f_{12} & \cdots & f_{1n} \\ f_{21} & f_{22} & \cdots & f_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ f_{k1} & \tilde{f}_{k2} & \cdots & f_{kn} \end{bmatrix} \end{array} \tag{6.13}$$

Since n attributes may be measured in different ways, the decision matrix D needs to be normalised. This step transforms various attribute dimensions into the non-dimensional attributes, which allows comparison across the attributes. The normalised attributes can be obtained by using Equation 6.3.

$$R = (r_{ij})_{m\times n} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_{kn} \end{array} \begin{array}{c} \begin{array}{cccc} AT_1 & AT_2 & \cdots & AT_n \end{array} \\ \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{k1} & r_{k2} & \cdots & r_{kn} \end{bmatrix} \end{array} \tag{6.14}$$

Step 2: *Construct weighted normalised decision matrix.* The weighted normalised decision matrix can be constructed by multiplying each element r_{ij} by its associated weight w_i:

$$v_{ij} = w_i \times r_{ij} \quad i = 1,2,\cdots,k; \; j = 1,2,\cdots,n \tag{6.15}$$

Step 3: *Determine ideal and negative ideal solutions.* Let the positive ideal solution A^+, and the negative ideal solution A^- be defined in terms of the weighted normalised values:

$$A^+ = \{v_1^+, v_2^+, \ldots, v_i^+, \ldots, v_k^+\} \text{ where } v_i^+ = \{\max v_{ji}, i \in J_1; \min v_{ji}, i \in J_2\}, \tag{6.16}$$

$$A^- = \{v_1^-, v_2^-, \ldots, v_i^-, \ldots, v_k^-\} \text{ where } v_i^- = \{\min v_{ji}, i \in J_1; \max v_{ji}, i \in J_2\}, \tag{6.17}$$

where J_1 is the set of the benefit attributes and J_2 is the set of cost attributes.

The distance of each alternative from positive ideal solution (D_i^+) and negative ideal solution (D_i^-) can be obtained by using Equations 6.18 and 6.19 respectively.

$$D_i^+ = \sqrt{\sum_{i=1}^{k} (v_{ij} - v_i^+)^2}, j = 1,2,\ldots,n \tag{6.18}$$

$$D_i^- = \sqrt{\sum_{i=1}^{k} (v_{ij} - v_i^-)^2}, j = 1,2,\ldots,n \tag{6.19}$$

Step 4: *Calculate the Relative Closeness (RC) of each alternative to the ideal solution and produce the final ranking.* The ranking of alternatives is determined following the RC calculation. This allows the decision makers to choose the most rational alternative. RC can be obtained by using Equation 6.20.

$$RC = \frac{D_i^-}{D_i^- + D_i^+} \tag{6.20}$$

However it should be noted that, the notion of RC may lead to inconsistency (Li, 2007). Given two alternatives i and k, then alternative i is better than k if $RC_i > RC_k$.

$$\frac{D_i^-}{D_i^- + D_i^+} > \frac{D_k^-}{D_k^- + D_k^+}$$

The above equation holds, if one of the conditions A, B and C is satisfied:

(A) $D_i^+ < D_k^+$ and $D_i^- > D_k^-$

(B) $D_i^+ > D_k^+$ and $D_i^- > D_k^-$ but $D_i^+ < \frac{D_k^+ \times D_i^-}{D_k^-}$

(C) $D_i^+ < D_k^+$ and $D_i^- < D_k^-$ but $D_i^- > \frac{D_k^- \times D_i^+}{D_k^+}$

Condition (A) corresponds to the principle of the TOPSIS method as alternative i is better than alternative k as it is closer to the PIS and farther from the NIS. However, condition (B) allows alternative i to be better than alternative k even though alternative i is farther from the PIS than alternative k. Condition (C) allows alternative i to be better than alternative k even though alternative i is closer to the NIS than alternative k.

As aforementioned, TOPSIS ranks the alternatives according to their distances from ideal and negative ideal solutions, i.e. the best alternative has simultaneously the shortest distance from the ideal solution and farthest distance from negative ideal solution. In the previous section, it is shown that this statement is vague in sense that it does not provide a precise definition of the relative closeness to the negative and ideal solutions. A new model is proposed to solve the issue.

In this context, the model proposed by Zimmermann & Zysno (1985) is used to determine the membership of an alternative that has the shortest distance from the ideal solution and that of the alternative that has the farthest distance from the negative ideal solution. According to this model, the membership of the former set is defined as a function of the distance (D_i^+) between a given alternative i and the ideal solution, and it is represented by Equation 6.21.

$$\mu^+ = \frac{1}{1+D_i^+} \tag{6.21}$$

(D_i^+) is measured by the euclidean distance. The membership of alternative from the negative ideal solution can also be defined, as a simple extension of the Zimmermann & Zysno (1985) model. Distance (D_i^-) between the given alternative i and the negative ideal solution is given as follows:

$$\mu^- = 1 - \frac{1}{1+D_i^-} = \frac{D_i^-}{1+D_i^-} \tag{6.22}$$

Yager (1980) suggested a class of intersection connectives as follows. Assume that A and B are subsets of X with membership values of μ^A and μ^B respectively. A general class of intersections is defined as follows:

$$A \cap B = C \text{ where } \mu^c = 1 - \min[1, (1-\mu^A)^P + (1-\mu^B)^P]^{\frac{1}{P}} \text{ for } P \geq 1. \tag{6.23}$$

The following properties can be concluded from this definition:

1. If $P \to \infty$, then $\mu^C = \min(\mu^A, \mu^B)$ (Zadeh connective)
2. If $P = 1$, then $\mu^C = \max[0, (\mu^A + \mu^B - 1)]$ (Lukasiewicz connective)

The parameter P is inversely related to the strength of the "and" operation. P is an inverse measure of how strong the "and" operation is meant. It must be noted that $\mu^+ \cap \mu^-$ is a monotonically decreasing function of P. Thus, as P decreases, the strength of the "and" operation increases (Yager, 1980).

According to the intersection connectives proposed by Yager (1980) RC can be obtained by Equation 6.24.

$$RC = \mu^{+\cap-} = 1 - \min[1, (1-\mu^+)^P + (1-\mu^-)^P]^{\frac{1}{P}} \text{ for } P \geq 1. \tag{6.24}$$

where μ^+ and μ^- are defined by Equations 6.22 and 6.23 respectively. Different values of P are connected with different behavioural patterns of decision makers uncertainty. In particular, higher values of P correspond to situation where decision makers increasingly take into account the worst characterization of an alternative, where as lower values of P correspond to situations where decision makers consider closeness to the best characterization of an alternative with increasing "strength". For example, assume the case of two alternatives i and j with memberships of $C_i = (0.3,0.6)$ and $C_j = (0.2,0.9)$ respectively. Then the ratings that would be produced for different values of parameter P are shown in Table 6.4.

Table 6.4 Ranking of two alternatives for different values of P

P	$C_i = (0.3,0.6)$	$C_j = (0.2,0.9)$
1	0.000 (2)	0.100 (1)
2	0.194 (1)	0.194 (1)
∞	0.300 (1)	0.200 (2)

The example depicted in Table 6.4 demonstrates that if $P = \infty$ a decision maker would rank alternative C_i higher whereas if $P = 1$ a decision maker would rank alternative C_j higher. Therefore, the proposed class of methods includes an extreme instance $(P = \infty)$ corresponding to situations where decision makers take into account only the worst characterization of an alternative, i.e. decision makers prefer alternatives that make as much profit as possible.

6.4.6 Validation of the FTOPSIS methodology

Validation is an important aspect of this methodology as it will provide a reasonable amount of confidence to the result of the proposed model. In this particular study a sensitivity analysis for partial validation of the model has been developed. Sensitivity analysis is conducted by considering three rules. In the first and second rules weights of attributes are changed and the expected output results are investigated. Third rule considers the final ranking result by considering different P values.

Rule 1: An increase/decrease in the weight of attributes should certainly result in changing of output. It should be noted that the sum of weights must be 1.

Rule 2: If weights of all cost attributes (negative attributes) and benefit attribute (positive attributes) are considered 0 and 1 respectively, the output result must be dependent on the positive attribute (e.g. Reliability (REL)) of alternatives. It means that the alternatives with the highest and lowest REL values are ranked as the first and last alternatives respectively.

Rule 3: Different P values must result in different outcomes. $P=1$ and $P=\infty$ are two extreme values. Therefore, the result of ranking for $P=1$ and $P=\infty$ must be different. It is expected that after certain values of P the ranking results remain unchanged in spite of different membership values.

6.5 Case study

The main aim of this section is to demonstrate how the proposed methodology can be applied to select the most rational RCO for offshore gas wells. Selection of the best RCO is made on the basis of one objective and three subjective attributes. Capital Cost (CC), Insurance Cost (IC), Reliability (REL) and Consequence (CON) are chosen, because they are regarded as the most significant attribute associated with well barrier based on extensive literature survey (Spouge, 1993; Erikvinnem, 2000; Corneliussen, 2006). Since it is useful to develop a hierarchical structure showing the overall objective, the attributes and alternatives in such a hierarchy for selection of the best RCO are shown in Figure 6.4.

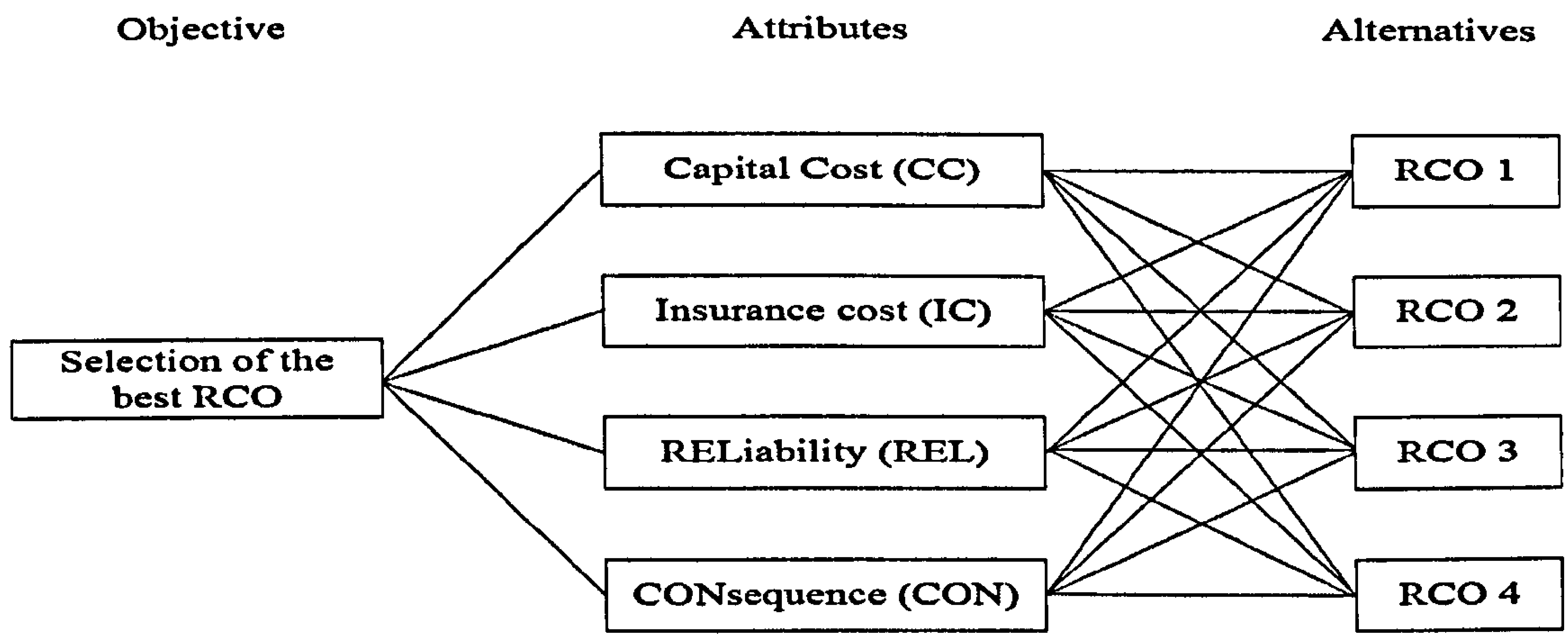


Figure 6.4 Decision hierarchy for selection of the best RCO

There are basically two types of attribute for a selection problem, namely subjective and objective attributes. If an assessment of an alternative with respect to an attribute is from real field data, this kind of attribute is called an objective attribute. When experts' opinions for an alternative with respect to an attribute are fuzzy estimates, then this attribute is called a subjective attribute. In an MADM problem, subjective and objective attributes can be divided into two classes. The first class is cost (the larger, the less preferred) and the other is benefit (the larger, the more preference). Attribute properties such as the type of attribute and type of assessment are summarized in Table 6.5.

Table 6.5 Attribute properties of case study

Attributes	Type of assessment	Type of attribute	
REL	Linguistic term	Benefit	Subjective
CON	Linguistic term	Cost	Subjective
CC	Real data	Cost	Objective
IC	Linguistic term	Cost	Subjective

6.5.1 Rating stage calculation

The alternatives in the case study are evaluated by a group of 3 experts, with respect to the subjective attributes. Since the only objective attribute of the decision problem is CC, the rating for this attribute does not need to be estimated and aggregated by the experts. For the rest of the attributes, the experts' linguistic judgments are transformed into their corresponding fuzzy numbers by using Table 5.4. RCO2 and RCO4 are considered as repairing the primary and secondary barriers respectively. It should be noted that valves, production packers and annulus are not repairable items; therefore, the CC and insurance premium must be considered the same as cost of replacing them. For IC and REL the experts express their opinions with respect to each WBE, but CON is rated with respect to well barriers. The three experts' judgments are presented for IC, CON and REL in Tables 6.6 to 6.8 respectively.

Table 6.6 Expert evaluations of the four alternatives with respect to IC

WBEs	RCO 1	RCO 2
Primary well barrier		
1. Production packer	Expert 1(L),Expert 2 (VL),Expert 3 (L)	Expert 1(L),Expert 2 (VL),Expert 3 (L)
2. SCSSV	Expert 1(M),Expert 2 (M),Expert 3(H)	Expert 1(M),Expert 2 (M),Expert 3(H)
3.Completion string	Expert 1(L),Expert 2 (L),Expert 3(L)	Expert 1(M),Expert 2 (L),Expert 3(H)
	RCO 3	RCO 4
Secondary well barrier		
1. Casing cement	Expert 1(L),Expert 2(VL),Expert 3(L)	Expert 1(M),Expert 2(M),Expert 3(L)
2. Casing	Expert 1(L),Expert 2(L),Expert 3(VL)	Expert 1(L),Expert 2(M),Expert 3(M)
3. Tubing hanger	Expert 1(VL),Expert 2(L),Expert 3(L)	Expert 1(M),Expert 2(L),Expert 3(M)
4. Well head	Expert 1(L),Expert 2(M),Expert 3(L)	Expert 1(M),Expert 2(H),Expert 3(H)
5. Production tree	Expert 1(L),Expert 2(L),Expert 3(M)	Expert 1(H),Expert 2(H),Expert 3(H)
6. Annulus valve	Expert 1(L),Expert 2(VL),Expert 3(L)	Expert 1(M),Expert 2(L),Expert 3(VL)

Table 6.7 Expert evaluations of four alternatives with respect to CON

WBEs	RCO1	RCO 2
Primary well barrier	Expert 1(H),Expert 2(H),Expert 3(M)	Expert 1(H),Expert 2 (H),Expert 3 (H)
	RCO 3	RCO 4
Secondary well barrier	Expert 1(H),Expert 2(H),Expert 3(H)	Expert 1(H),Expert 2(H),Expert 3(VH)

Table 6.8 Expert evaluation of four alternatives with respect to REL

WBEs	RCO 1	RCO 2
Primary well barrier		
1. Production packer	Expert 1(VH),Expert 2(VH),Expert 3(VH)	Expert 1(H),Expert 2(H),Expert 3(H)
2. SCSSV	Expert 1(VH),Expert 2(VH),Expert 3(VH)	Expert 1(H),Expert 2(H),Expert 3(VH)
3.Completion string	Expert 1(H),Expert 2(VH),Expert 3(H)	Expert 1(M),Expert 2(M),Expert 3(M)
	RCO 3	RCO 4
Secondary well barrier		
1. Casing cement	Expert 1(H),Expert 2(VH), Expert 3(H)	Expert 1(M),Expert 2(M),Expert 3(H)
2. Casing	Expert 1(VH),Expert 2(VH),Expert 3(VH)	Expert 1(VH),Expert 2(VH),Expert 3(VH)
3. Tubing hanger	Expert 1(VH),Expert 2(VH),Expert 3(VH)	Expert 1(VH),Expert 2(VH),Expert 3(VH)
4. Well head	Expert 1(VH),Expert 2(VH),Expert 3(VH)	Expert 1(H),Expert 2(H),Expert 3(H)
5. Production tree	Expert 1(VH),Expert 2(VH),Expert 3(VH)	Expert 1(H),Expert 2(H),Expert 3(H)
6. Annulus valve	Expert 1(H),Expert 2(H),Expert 3(H)	Expert 1(H),Expert 2(H),Expert 3(H)

6.5.2 Calculating weights of attributes and experts

6.5.2.1 Estimating weights of attributes

Fuzzy set theory and AHP have been used to estimate the weights of all the attributes and experts. Table 4.6 has been used to make a pair-wise comparison. Five linguistic terms are used ranging from equal importance to absolute importance. A 4×4 pair-wise comparison matrix is developed to obtain the weights of all the attributes. $\tilde{A}$ is the pair-wise comparison matrix expressing the quantified judgment with regard to the relative importance of the attributes. For example, two experts estimated that attributes of *REL* and *CC* are of "equal importance" and their judgments are then translated to a fuzzy number of $(1,1,2)$. One expert considered that *REL* is of "strong importance" in comparison with event *CC* which corresponds to fuzzy number $(4,5,6)$. Using Equation 6.4, elements in $\tilde{a}_{13}$ and $\tilde{a}_{31}$ pair-wise comparison can be obtained as follows:

$$\tilde{a}_{13} = \frac{1}{3}((1,1,2)\oplus(1,1,2)\oplus(4,5,6)) = (1.66,2.33,3.33)$$

$$\tilde{a}_{31} = \frac{1}{\tilde{a}_{13}} = \frac{1}{(1.66,2.33,3.33)} = (0.3,0.43,0.6)$$

A 4×4 fuzzy pairwise comparison matrix $\tilde{A}$ can be constructed as follows:

$$\tilde{A} = \begin{array}{c} \\ REL \\ CON \\ CC \\ IC \end{array} \begin{array}{cccc} REL & CON & CC & IC \\ \left[\begin{array}{cccc} \tilde{1} & (1,1,2) & (1.66,2.33,3.33) & (4,5,6) \\ (0.5,1,1) & \tilde{1} & (1.33,1.66,2.66) & (4,5,6) \\ (0.3,0.43,0.6) & (0.37,0.6,0.75) & \tilde{1} & (1,1,2) \\ (0.16,0.2,0.25) & (0.16,0.2,0.25) & (0.5,1,1) & \tilde{1} \end{array}\right] \end{array}$$

Using the geometric mean technique, each attribute weight can be calculated by using Equations 6.7 and 6.8; Table 6.9 presents the weights of all the attributes.

$$\tilde{f}_{REL} = ((1,1,1)\otimes(1,1,2)\otimes(1.66,2.33,3.33)\otimes(4,5,6))^{\frac{1}{4}} = \left((1\times1\times1.66\times4)^{\frac{1}{4}},(1\times1\times2.33\times5)^{\frac{1}{4}},(1\times2\times3.33\times6)^{\frac{1}{4}}\right)$$

$$\tilde{f}_{REL} = (1.6,1.84,2.51),\ \tilde{f}_{CON} = (1.28,1.7,2),\ \tilde{f}_{CC} = (0.58,0.72,0.98),\ \tilde{f}_{IC} = (0.34,0.45,0.5)$$

$$\tilde{w}_{REL} = \frac{\tilde{f}_{REL}}{\tilde{f}_{REL}+\tilde{f}_{CON}+\tilde{f}_{CC}+\tilde{f}_{IC}} = \frac{(1.6,1.84,2.51)}{(3.8,4.71,5.99)} = \left(\frac{1.6}{5.99},\frac{1.84}{4.71},\frac{2.51}{3.8}\right) = (0.27,0.39,0.66)$$

Table 6.9 Weights of attributes

Fuzzy weight of attributes	Defuzzified weight	Normalized weight of attribute
$\tilde{w}_{REL} = (0.27,0.39,0.66)$	$DF\ w_{REL}$=0.44	w_{REL}=0.415
$\tilde{w}_{CON} = (0.2,0.36,0.56)$	$DF\ w_{CON}$=0.36	w_{CON}=0.34
$\tilde{w}_{CC} = (0.09,0.15,0.26)$	$DF\ w_{CC}$=0.17	w_{CC}=0.16
$\tilde{w}_{IC} = (0.05,0.09,0.13)$	$DF\ w_{IC}$=0.09	w_{IC}=0.085

6.5.2.2 Estimating weights of experts

Three experts are selected to make judgments with respect to the subjective attributes. The experts' weight can be obtained by using Table 4.6, Equations 6.11 and 6.12. Table 6.10 presents the experts' weights.

Table 6.10 Weights of experts

Expert number	PP	ST (Year)	EL	Weighting factor	Weighting score
1	Senior academic	10-19	PhD	5+3+5=13	0.37
2	Junior academic	20 – 29	Master	4+4+4=12	0.34
3	Engineer	20 – 29	Bachelor	3+4+3=10	0.29
				Total=35	Total=1

6.5.3 Aggregation of subjective attributes

In this step, all the ratings are aggregated for each subjective attribute. As mentioned earlier the subjective attributes are IC, CON and REL. The aggregation calculations for IC, CON and REL are given in Table 6.11 to Table 6.15 respectively. Aggregation of each RCO with respect to IC is performed in two stages. The first stage is to obtain rating of judgment of each expert for each RCO. As an example, the calculation of Expert 1 judgment for RCO1 is given in Table 6.11.

Table 6.11 Aggregation of judgment of Expert 1 for RCO1 with respect to IC

WBEs				
1.Production packer	0.1	0.25	0.25	0.4
2.SCSSV	0.3	0.5	0.5	0.7
3.Completion string	0.1	0.25	0.25	0.4
S (WBE1&WBE2) S (WBE1&WBE3) S (WBE2&WBE3)	0.75 1 0.75			
AA (WBE1) AA (WBE2) AA (WBE3)	0.875 0.75 0.875			
RA (WBE1) RA (WBE2) RA (WBE3)	0.35 0.3 0.35			
CC (WBE1) CC (WBE2) CC (WBE3)	0.35 0.3 0.35			
Aggregation of E1	0.16	0.325	0.325	0.49

The second stage is to aggregate the judgment of the three experts on IC for the RCOs. Table 6.12 presents the aggregation calculation of the three experts' judgments on IC.

Table 6.12 Aggregation of three experts rating with respect to IC

Expert 1 (E1)		0.16	0.325	0.325	0.49
Expert 2 (E2)		0.13	0.245	0.278	0.427
Expert 3 (E3)		0.225	0.375	0.375	0.525
S (E1&E2) S (E1&E3) S (E2&E3)	0.945 0.95 0.895				
AA (E1) AA (E2) AA (E3)	0.947 0.920 0.922				
RA (E1) RA (E2) RA (E3)	0.339 0.329 0.330				
CC (E1) CC (E2) CC (E3)	0.354 0.334 0.310				
Weight of expert 1		0.37			
Weight of expert 2		0.34			
Weight of expert 3		0.29			
Aggregation for RCO1		0.170	0.313	0.324	0.479

The aggregation of the three expert judgments for RCO1 with respect to CON is presented in Table 6.13.

Table 6.13 RCO1 aggregation with considering CON

Expert 1 (E1)		0.6	0.75	0.75	0.9
Expert 2 (E2)		0.6	0.75	0.75	0.9
Expert 3 (E3)		0.3	0.5	0.5	0.7
S (E1&E2) S (E1&E3) S (E2&E3)	1 0.75 0.75				
AA (E1) AA (E2) AA (E3)	0.875 0.875 0.75				
RA (E1) RA (E2) RA (E3)	0.35 0.35 0.3				
CC (E1) CC (E2) CC (E3)	0.36 0.345 0.295				
Weight of expert 1		0.37			
Weight of expert 2		0.34			
Weight of expert 3		0.29			
Aggregation for RCO1		0.511	0.676	0.676	0.841

Aggregation of the REL estimates for each RCO can be performed in two stages. The first stage is to obtain a rating for each expert judgment for each RCO. A well barrier is dependent on one or several WBEs to fulfil its function. The REL of a series structure can be obtained by multiplying the REL values of all its components. Therefore, the reliability of a well barrier can be obtained by multiplying the REL judgments of the WBEs (Table 6.8). As an example, an estimation of expert 1 judgment on REL for RCO1 is given in Table 6.14.

Table 6.14 Expert 1 judgment with respect to REL

WBEs	RCO 1
1. Production packer	Expert 1(VH)
2. SCSSV	Expert 1(VH)
3.Completion string	Expert 1(H)
REL estimation	$REL = VH \times VH \times H = (0.384, 0.607, 0.75, 0.9)$

In the second stage, the aggregation of the three experts' judgments for RCO 1 on REL is presented in Table 6.15.

Table 6.15 Aggregation of the three experts' judgment REL for RCO1

Expert 1 (E1)		0.384	0.607	0.75	0.9
Expert 2 (E2)		0.512	0.729	1	1
Expert 3 (E3)		0.384	0.607	0.75	0.9
S (E1&E2) S (E1&E3) S (E2&E3)	0.85 1 0.85				
AA (E1) AA (E2) AA (E3)	0.925 0.85 0.925				
RA (E1) RA (E2) RA (E3)	0.343 0.313 0.343				
CC (E1) CC (E2) CC (E3)	0.356 0.326 0.316				
Weight of expert 1		0.37			
Weight of expert 2		0.34			
Weight of expert 3		0.29			
Aggregation for RCO1		0.425	0.646	0.831	0.932

Aggregations of judgment of all experts for each RCOs with respect to proposed attributes are demonstrated in Appendix 4.

6.5.4 Transformation of subjective attributes into crisp values

As aforementioned, CC is the only objective attribute. The CC estimates of all the WBEs are based on the values for a well under a pressure of 10000 psi. Such values are in units of US $ and shown in Table 6.16. These prices are obtained from Iranian Offshore Engineering and Construction Company (IOEC).

Table 6.16 CC for WBEs

WBEs	RCO 1	RCO 2
Primary well barrier		
1. Production packer	25000	25000
2. SCSSV	120000	120000
3.Completion string	45000	15000
Total cost of each RCO	190000	160000
	RCO 3	RCO 4
Secondary well barrier		
1. Casing cement	20000	20000
2. Casing	50000	50000
3. Tubing hanger	80000	80000
4. Well head	210000	85000
5. Production tree	350000	100000
6. Annulus valve and access line	20000	20000
Total cost of each RCO	730000	355000

All the subjective data is converted into crisp values using Equation 5.15. The decision matrix, including all objective values and aggregation of subjective ratings for each RCO under consideration is obtained and shown in Table 6.17. As demonstrated in Table 6.17, the decision matrix is a combination of subjective and objective values. All the subjective values are converted into their corresponding crisp values by using Equation 5.15 and shown in Table 6.18.

Table 6.17 Decision matrix

	REL (Benefit)	CON (Cost)	CC (Cost)	IC (Cost)
RCO1	(0.425,0.646,0.831,0.932)	(0.511,0.676,0.676,0.841)	190000	(0.17,0.313,0.324,0.479)
RCO2	(0.12,0.3,0.31,0.59)	(0.6,0.75,0.75,0.9)	160000	(0.27,0.426,0.44,0.6)
RCO3	(0.16,0.393,0.624,0.84)	(0.6,0.75,0.75,0.9)	730000	(0.17,0.314,0.325,0.48)
RCO4	(0.06,0.2,0.24,0.45)	(0.66,0.795,0.825,0.93)	355000	(0.323,0.49,.05,0.67)

Table 6.18 Crisp value of decision matrix

	REL (Benefit)	CON (Cost)	CC (Cost)	IC (Cost)
RCO1	0.705	0.676	190000	0.323
RCO2	0.336	0.75	160000	0.435
RCO3	0.503	0.75	730000	0.322
RCO4	0.243	0.800	355000	0.496

6.5.5 Selecting stage

The TOPSIS procedure is applied to the four alternatives to obtain the best RCO and ranking orders.

6.5.5.1 Normalization of the decision matrix

In this step, the normalisation is carried out for the decision matrix shown in Table 6.18. The normalised attributes can be obtained using Equation 6.3. The normalised decision matrix is shown in Table 6.19.

Table 6.19 Fuzzy normalised decision matrix

	REL (Benefit)	CON (Cost)	CC (Cost)	IC (Cost)
RCO1	0.735	0.454	0.224	0.493
RCO2	0.351	0.500	0.188	0.542
RCO3	0.523	0.500	0.860	0.401
RCO4	0.253	0.536	0.418	0.618

6.5.5.2 Constructing weighted normalised decision matrix

The weighted normalised fuzzy decision matrix can be obtained by employing Equation 6.20. For example, the weighted normalised REL of RCO1 is obtained as follows:

$$v_{11} = 0.415 \times 0.735 = 0.305$$

The weighted normalised fuzzy decision matrix is shown in Table 6.20.

Table 6.20 Weighted normalised decision matrix

	REL (Benefit)	CON (Cost)	CC (Cost)	IC (Cost)
RCO1	0.305	0.154	0.036	0.041
RCO2	0.145	0.17	0.030	0.046
RCO3	0.217	0.17	0.137	0.034
RCO4	0.104	0.182	0.067	0.052

6.5.5.3 Obtaining the distances of an alternative from ideal and negative ideal solutions

Determination of the positive-ideal solution can be easily made by taking the largest element for each benefit attribute and the smallest element for each cost attribute. The negative ideal solution is simply the opposite formation of the positive-ideal solution. The positive and negative ideal solutions are given in Table 6.21.

Table 6.21 PIS and NIS

	Positive Ideal Solution (PIS)	Negative Ideal Solution (NIS)
REL	0.305	0.104
CON	0.154	0.182
CC	0.030	0.137
IC	0.034	0.052

The distances and closeness membership functions from each RCO to PIS and NIS are calculated for all the alternatives by employing Equations 6.23, 6.24, 6.26 and 6.27 respectively. An example highlighting the calculation process for RCO1 is given below and the results for all the RCOs are shown in Table 6.22.

$$D^{+} = \sqrt{(0.305-0.305)^2+(0.154-0.154)^2+(0.030-0.33)^2+(0.034-0.041)^2} = 0.009$$

$$\mu^{+} = \frac{1}{1+0.009} = 0.99$$

$$D^{-} = \sqrt{(0.104-0.305)^2+(0.182-0.154)^2+(0.137-0.33)^2+(0.052-0.041)^2} = 0.226$$

$$\mu^{-} = \frac{0.226}{1+0.226} = 0.184$$

Table 6.22 Distance and closeness values of each alternative from PIS and NIS

	RCO1	RCO2	RCO3	RCO4
D^{+}	0.009	0.160	0.112	0.206
D^{-}	0.226	0.115	0.114	0.070
μ^{+}	0.99	0.861	0.899	0.829
μ^{-}	0.184	0.104	0.102	0.066

6.5.5.4 Calculating the RC of each alternative from the ideal solution

The RC values of the four RCOs at $P = 1,2,3 \text{ and} \infty$ can be obtained by using Equation 6.29 and the result is shown in Table 6.23.

Table 6.23 RC values of the RCOs

P	RCO1	RCO2	RCO3	RCO4
1	0.175	0	0.001	0
2	0.182	0.093	0.094	0.051
3	0.183	0. 101	0.100	0.063
∞	0.184	0.104	0.102	0.066

It can be seen from Table 6.23 that each instance of the proposed method yields different values for RCOs corresponding to different behavioral patterns of decision makers. Indeed when $P = \infty$, RCO1 is ranked as the best alternative followed by RCO2, RCO3 and RCO4 respectively. RCO1 is characterised by the maximum of negative membership value (0.184) corresponding to decision makers who prefer alternatives that make not only as much profit as possible but also as much as risk as possible.

As parameter P decreases, rankings correspond to decision makers that take into account the best characterisation of an alternative with an increasing strength. When $P = 2$, the ranking of the RCO2 and RCO3 is reversed as the higher membership value μ^+ of RCO3 $(0.899 > 0.861)$ compensates it's lower membership value μ^- $(0.104 > 0.102)$ leading to a completely different rank order compared with the instance of $P = \infty$.

6.5.6 Validation of FTOPSIS model

In the first rule, analysis is performed by investigating the values and ranking of the alternatives due to the weight changes. The weights of all the attributes are considered to be of equal importance. Table 6.24 shows that the values of the RCOs are changed due to the weight changes.

Table 6.24 Rating of RCOs by considering equal weights for attributes

P	RCO1	RCO2	RCO3	RCO4
1	0 .144	0.053	0	0
2	0.167	0.141	0.067	0.091
3	0.168	0.144	0.078	0.097
∞	0.169	0.146	0.080	0.099

In the second rule, the weights of 1 and 0 are considered for positive attribute (REL) and negative attributes (CON, CC and IC) respectively. The alternatives (RCOs) with higher REL values should have better ranking results. Therefore, the ranking result must be RCO1 (1^{ST}), RCO3 (2^{ND}), RCO2 (3^{RD}) and RCO4 (4^{TH}). Table 6.25 results confirm the aforementioned expectation.

Table 6.25 Ranking results with considering weight of one for REL and zero for negative attribute

P	RCO1	RCO2	RCO3	RCO4
1	0.325 (1)	0.001 (3)	0.037 (2)	0 (4)
2	0.325 (1)	0.047 (3)	0.193 (2)	0 (4)
3	0.325 (1)	0.079 (3)	0.207(2)	0 (4)
∞	0.325 (1)	0.089 (3)	0.219 (2)	0 (4)

In the third rule, model validation is investigated by considering five instances for P (1, 1.5, 2, 3, 10 and ∞). Table 6.26 demonstrates that each instance of P results in different ratings values. Six instances of P are selected randomly.

Table 6.26 Ratings value with considering different P instances

p	RCO1	RCO2	RCO3	RCO4
1	0.174(1)	0(3)	0.001(2)	0(3)
1.5	0.181(1)	0.067(3)	0.071(2)	0.018(4)
2	0.182(1)	0.093(3)	0.094(2)	0.051(4)
3	0.183(1)	0. 101(2)	0.100(3)	0.063(4)
10	0.183(1)	0.103(2)	0.101(3)	0.065(4)
∞	0.184(1)	0.104(2)	0.102(3)	0.066(4)

As explained in the validation section, $P=1$ and $P=\infty$ should have certainly different ranking results. RCOs ranking in Table 6.26 can satisfy the aforementioned expectation.

6.6 Conclusion

This chapter presents an effective FMADM method, which is suitable for solving multiple attribute group decision making problems under a fuzzy environment where the information available is subjective and imprecise. The proposed method enables a group of decision makers to incorporate and aggregate subjective opinions. The basic principle of the TOPSIS method is that the chosen alternative should have the farthest distance from the NIS and shortest distance from the PIS. However, such chosen alternative is not always closest to the ideal solution if it is obtained by using Equation 6.25. In this chapter a new method is proposed to balance the shortest distance from the

PIS and the farthest distance from the NIS. Such a FMADM can be employed as an alternative tool for situations where both qualitative and quantitative data has to be synthesized. By using the model developed and presented here, offshore well designers and operators can choose the best RCO based on the requirements of multiple attributes including REL, CON and costs.

Chapter 7

Conclusion and implications

Summary

This chapter briefly summaries that the risk assessment and decision making approaches and techniques presented in the previous chapters would be of benefit in OGSS safety, operation and management. In summary, it is concluded that the developed models can be integrated to formulate a platform to facilitate risk assessment and safety management of OGSS operations without jeopardising the efficiency of system operations in a variety of situations where traditional techniques cannot be applied with confidence. The areas, which require more effort to be paid for the improvement of the developed approaches, are outlined.

7.1 Conclusion

Offshore safety has evolved in a reactive manner toward a risk-based goal-setting approach since 1990s due to public concern following several catastrophic disasters. Traditional risk assessment techniques are capable of handling risks with confidence on the premise that historical data is available. However, such techniques may not genuinely reflect risk results in circumstances where the lack of data exists or the information available consists of high level of uncertainty. Accordingly, it is necessary for a study of safety in an OGSS to enable the higher risk areas with scarce data for use to be addressed.

In risk assessment and safety management, the issue of, "How to manage uncertainty", is a major concern. However, the causes of uncertainty are diverse. Thus, regardless of what approach to be applied, it is always dependent upon human judgment to manage such negative effects. In other words, the deficiencies of risk modelling resulting from the lack of information or a high level of uncertainty must be made up by means of general evaluation capacity of humans, who are able to grasp the essence of an object, even if it is vague and unclear. Therefore, the experience of experts consulted is crucial, since the cornerstone of such uncertainty treatment is the professional judgment of such personnel.

The risk assessment and safety management frameworks proposed based on fuzzy set theory in this study are capable of handling imprecise, ambiguous and qualitative information from experts in a consistent manner. These can be regarded as reliable reasoning processes with capability of quantifying the judgement from experts who express their opinions qualitatively. In addition, the linguistic terms employed in assessments are developed in a consensus manner. Such consensus assessments with regard to linguistic terms provide the compatible throughout the risk assessment and safety management process.

Following the identification of the research needs, this PhD study has developed one data model and three analytical models capable of performing risk assessment and safety management with confidence under the aforementioned circumstances. Such frameworks have been demonstrated by three corresponding test cases with regard to the safety of OGSS operations. The frameworks have been developed in a generic sense to be applicable to deal with both engineering and managerial problems. They provide the basis for the generation of the various risk analysis methods and decision making procedures. In summary, these methods and techniques can be concluded as follows:

- Using OOA to deal with complexity of OGSSs and to provide a hierarchical structure of risk assessment.
- Applying FRA, AHP and ER to evaluate risks of objects, subsystems and an overall OGSS.
- Employing FFTA to identify critical components in an OGSS.
- Using FTOPSIS to select the best RCO for an OGSS.

It is also believed that these methods can be tailored to practical applications of dealing with safety problems in other industries, especially in situations where a high level of uncertainty exists. The implementation of the described approaches could have highly beneficial effect in real life. More specific description can be provided as follows:

1) A framework of aggregative risk assessment for representing the relationships of components, subsystems and an overall OGSS.

2) A framework of FTA for representing cause effect relationship of specific risks.

FRA is used to evaluate the framework of aggregative risk assessment for an OGSS. Three mathematical theories are combined for assessing the risk frameworks in Chapter 4. Fuzzy set theory is used to represent the characteristics of a hazard such as likelihood of occurrence and consequence severity. AHP is used to aggregate risks along the hierarchical structure to obtain the risk estimates associated with objects, subsystems and an overall OGSS. An ER approach is used to combine newly obtained data for the updating of existing risk estimates at any level of hierarchy. Risk analysts can use this information to compare risk levels of components and subsystems that contribute to the final aggregated risk. As demonstrated in Table 4.15, risk value of offshore gas well, offshore gas pipeline, offshore gas holder, compressor and OGSS are 0.17, 0.241, 0.12, 0.175 and 0.19 respectively. By considering the risk value and weight of each subsystem, the most critical subsystem can be identified. Offshore pipeline is selected as the most critical subsystem. The next step is to apply FFTA for identifying the most important MCSs of the most critical subsystem (offshore pipeline).

In the absence of excat data, it is necessary to work with subjective probabilities. Under these conditions, it is inappropriate to use coventional FTA. Therefroe, FFTA is proposed to capture the subjectivity. The result of FFTA are the liklihood of occurrence for specicific risks and importance measure of potential contributing factors. Application of FFTA in Chapter 5 shows that it is useful to identify critical MCSs for a specific risk. As shown in Table 5.12, all the critical MCSs are identified and ranked.

Results of Chapter 4 and Chapter 5 help the analyst to select RCOs for mitigating risk of the most critical subsystem and overall OGSS respectively. It is not financially possible to select all the proposed RCOs. Therefore, MADM by using FTOPSIS is tailored to select the best RCO from a finite number of RCOs. When dealing with RCO ranking/selecting, decision data available for MADM is usually fuzzy, crisp, or a combination of the two. FTOPSIS is proposed to handle both fuzzy and crisp data. When evaluating RCOs for enhancing the safety of an OGSS, there are many parameteres that need to be considered. On the basis of the test case in Chapter 6 involving the elements of REL, CC, IC and CON, it is reasonable to judge that the decision making model developed is capable of handling such MADM problems. The proposed method is particularly useful in circumstances where multiple experts are involved in a decision making process.

Since the test case in this study provide reasoanable results, it is felt that the analytical models developoped have the potential to imporve the safety of OGSSs. Such models can be applied indivually by the offshore pipeline industry particularly in circumstances where a lack of data exists or the data for use is associated with a high level of uncertainty. More importantly, these frameworks can be integrated to formulate a platform to facilitate risk assessment and safety mangement of OGSS operations without jeoparadising the efficeny of operations in variety of situations where traditional techniques may not be applied with confidence.

7.2 Recommendations for further research

In offshore safety, under circumstances where the lack of data or a high level of uncertainty exists, a large number of assumptions, judgments and opinions are involved subjectively in the reasoning process. Other than an approximate reasoning approach, new approaches capable of addressing uncertainty and combining expert judgment and empirical data should be developed. A Bayesian network model, for example, is a method that has the capability of incorporating expert judgment with historical data to evaluate risks. It provides intuitive visual representation with a sound mathematical basis in Bayesian probability, which captures genuine cause and effect relationship. Moreover, the technique facilitates a meaningful communication of uncertainty, allowing decisions to be made based on expected values. Such a technique is also capable of dealing with conditional probability problems.

Furthermore, when evaluating risks under circumstances of the scarcity of data perhaps due to the high level of costs in conducting a full-scale experimentation, the use of computer simulation may be potentially useful. It is worthwhile to note that some computer software facilitates the data compilation process.

The offshore industry is moving toward a risk-based goal-setting regime. This provides safety analysts with more flexibility to employ novel and the latest risk modelling and decision making techniques. Subjective modelling and approximate reasoning methods may be useful approaches. It may be beneficial if the novel techniques developed in this research could be further applied to facilitate risk modelling and decision making. Since the methodologies proposed in this research are generic in nature, such frameworks can be further verified for safety analysis outside the offshore pipeline industry. This will provide an added value to the promotion of their use in different industries.

This PhD research formulates a platform for OGSSs to improve the risk assessment and safety management of their operations. The principle implication of this is that the offshore pipeline industry will have to collect data for each component with regard to safety based on daily operations with the objective of continuous improvement of safety and efficiency.

References

Alim, S. (1988), "Application of Dempster-Shafer theory for interpretation of seismic parameters", *ASCE Journal of Structural Engineering*, Vol. 114, pp. 2070-2084.

An, M. (2007), "Risk assessment in railway safety management", *International Journal of Engineering and Technology*, Vol. 14, pp. 45-56.

An, M.; Huang, S. and Baker, J.C. (2007), "Railway risk assessment - the FRA and FAHP approaches: a case study of shunting at Waterloo depot", Proceedings of the Institute of Mechanical Engineers, Part F: *Journal of Rail and Rapid Transit*, Vol. 221, pp. 365-384.

Anandaligam, G. (1989), "A multiagent multiattribute approach for conflict resolution in acid rain impact mitigation", *IEEE Transactions on Systems, Man and Cybernetics*, Vol. 19, pp. 1142-1153.

Andrews, J.D. and Moss, R.T. (2002), *Reliability and risk assessment*, 2nd Ed, Professional Engineering Publishing, UK.

Ang, A.H. and Tang, W.H. (1984), *Probability concept in engineering planning and design*, John wiley sons, UK.

Aven, T. and Vinnem, J.E. (2007), *Risk management with applications from the offshore petroleum industry*, Springer London, UK.

Bendixen, L.M.; Neil, J.K. and Little A.D. (1984), "Chemical plant risk assessment using HAZOP and fault tree methods", *Plant/Operation Progress*, Vol. 3, pp. 179-184.

Bernatik, A. and Libisova, M. (2004), "Loss prevention in heavy industry: risk assessment of large gasholders", *Journal of Loss of Prevention in the Process Industry*, Vol. 17, pp. 271-278.

Bilgiç, T. and Turksen, I.B. (1999), "Measurement of membership functions: theoretical and empirical work", Chapter 3 in D. Dubois and H. Prade (eds) Handbook of Fuzzy Sets and Systems, *Fundamentals of Fuzzy Sets*, Vol. 1, pp. 195-232.

Black, J.J. and Megabit, O. (1995), "Simulation of complex manufacturing equipment reliability using object-oriented methods", *Reliability Engineering & System Safety*, Vol. 48, pp. 11-18.

Blooch, H.P. (2006), *A practical guide to compressor technology*, 2ND Ed, Wiley, US.

Boender, C.G.; Graan, J. and Lootsma, F.A. (1989), "Multi-criteria decision analysis with fuzzy pairwise comparisons", *Fuzzy Sets and Systems*, Vol. 29, pp. 133–143.

Booch, G. (1994), *Object-oriented analysis and design with applications*, 2nd Ed, the Benjamin/Cummings Publishing Company, Inc.

Bourgoyne, A.T.; Millheim, M.E. and Young, F.S. (2003), "Applied drilling engineering", *Society of Petroleum Engineering*, Vol. 9, pp. 1-23.

Bozdağ, C.E; Kahraman, C. and Ruan, D. (2003), "Fuzzy group decision making for selection among computer integrated manufacturing systems", *Computers in Industry*, Vol. 51, pp. 13-29.

Buckley, J.J. (1985), "Fuzzy hierarchical analysis", *Fuzzy Sets and Systems*, Vol. 17, pp. 233-247.

Büyüközkan, G.; Kahraman, C. and Ertay, T. (2004), "A fuzzy optimization model for QFD planning process using analytic network approach", *European Journal of Operational Research*, Vol. 171, pp. 390-411.

Cai, K.Y.; Wen, C. and Zhang, M. (1991), "Fuzzy states as a basis for a theory of fuzzy reliability in the possibility context", *Fuzzy Sets and Systems*, Vol. 42, pp. 17-32.

Chan, F. and Kumar, N. (2007), "Global supplier development considering risk factors using fuzzy extended AHP-based approach", *Omega*, Vol. 35, pp. 417-431.

Chang, D.Y. (1996), "Applications of the extent analysis method on fuzzy AHP", *European Journal of Operational Research*, Vol. 95, pp. 649-655.

CCPS. (2001), *Layer of protection analysis – simplified process risk assessment*, Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers, New York.

Chen, S.J. and Hwang, C.L. (1992), *Fuzzy multiple attribute decision making*, Springer – Verlag Berlin Heidelberg, Germany.

Chen, C. (2000), "Extensions of the TOPSIS for group decision-making under fuzzy environment", *Fuzzy Sets and Systems*, Vol. 114, pp. 1-9.

Chen, C.T. (2001), "A fuzzy approach to select location of the distribution center", *Fuzzy Sets and Systems,* Vol. 118, pp. 65-73.

Chen, S.M. (2001), "Fuzzy group decision making for evaluating the rate of aggregative risk in software development", *Fuzzy Sets and Systems*, Vol. 118, pp. 75-88.

Chen, L.; Wang, G.L. and Meng, H.R. (1995), "Fault tree analysis of an oil well pump", *Acta Petroleum Sinica*, Vol. 16, pp. 145-151.

Cheng, C. H. (1994), "Evaluating naval tactical missile systems by fuzzy AHP based on the grade value of membership function". *European Journal of Operational Research*, Vol. 96, pp. 343-350.

Cheng, C.H.; Yang, K.L. and Hwang, C.L. (1999), "Evaluating attack helicopters by AHP based on linguistic variable weight", *European Journal of Operational Research*, Vol. 116, pp. 423-43.

Cheng, C.H. and Mon, D.L. (1993), "Fuzzy system reliability analysis by interval of confidence", *Fuzzy Sets and Systems*, Vol. 56, pp. 29-35.

Corneliussen, K. (2006), *Well safety – risk control in the operational phase of offshore wells,* PhD thesis, School of Engineering, National Technique University Norway.

Corneliussen, K.; Sørli, F.; Brandanger, H.;Tenold, E.; Menezes, C.; Grimbert, B. and Owren, K. (2007), "Well integrity management system (WIMS) - a systematic way of describing the actual and historic integrity status of operational wells", SPE paper 110347, Society of Petroleum Engineers.

Courtois, P. (1985), "On time and space decomposition of complex structures", *Communications of the ACM*, Vol. 28, pp. 590-603.

Crossland, R.; Williams, J.H. and McMahon, C.A. (2003), "An object-oriented modelling framework for representing uncertainty in early variant design, *Research in Engineering Design*, Vol.14, pp.173-183.

Dempster, A. (1968), "A generalization of bayesian inference", *Journal of Royal Statistical Society*, Vol. 30, pp. 205-247.

Deng, H. (1999), "Multicriteria analysis with fuzzy pairwise comparison", *International Journal of Approximate Reasoning*, Vol. 21, pp. 215-31.

DETR (1995), *A guide to risk assessment and risk management for environmental protection*, Department of the Environment Transport and the Regions, available at (May 1, 1995), (http://www.defra.gov.uk/environment/risk/eramguide/02.htm).

DETR (2000), *Guidelines for environmental risk assessment and management*, Department of the Environment Transport and the Regions, available at (Aug 10, 2000), (http://www.defra.gov.uk/environment/risk/eramguide/index.htm).

DOCEP (2006), *Petroleum pipeline safety*, Department of Consumer and Employment Protection, Government of Western Australia, available at (July 20, 2006), (http://www.docep.wa.gov.au/resourcessafety/sections/Petroleum/pages/Petroleum_Pipeline_S.html).

Dong, H.Y. and Yu, D.U. (2005), "Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis", *Journal of Loss Prevention in the Process Industries*, Vol. 18, pp. 83-88.

Eleye-Datubo, A.G. (2006), *Investigated risk based modelling of safety critical marine and offshore applications*, PhD Thesis, School of Engineering, Liverpool John Moores University.

Elshorbagy, A. and Ormsbee, L. (2006), "Object-oriented modelling approach to surface water quality management", *Environmental Modelling & Software*, Vol. 21, pp. 689-698.

Embly, D.W.; Kurtz, B.D. and Woodfield, S.N. (1992), *Object-Oriented System Analysis: A Model-Driven Approach*, Yourdon Press.

Erensal, Y.C.; Öncan, T. and Demircan, M.L. (2006), "Determining key capabilities in technology management using fuzzy AHP: A case study of turkey", *Information Sciences*, Vol. 176, pp. 2755-2770.

Ford, D. and Sterman, J.D. (1998), "Expert knowledge elicitation to Improve mental and formal models", *Systems Dynamics Review*, Vol. 14, pp. 309–340.

Furuta, H. and Shiraishi, N. (1984), "Fuzzy importance in fault tree analysis", *Fuzzy Sets and Systems,* Vol. 12, pp. 205-213.

Gall, J. (1986), *SYSTEMANTICS: The Underground Text of Systems Lore. How Systems Really Work and How They Fail*, 2nd Ed, General Systemantics Press.

Garrick, B.J.; Hall, J.E.; Kilger, M.; Mcdonald, J.C.; Probst, P.S.; Parker, E.R.; Rosenthall, R.; Trivelpiece, W.; Arsadle, L.A. and Zebroski, E.L. (2005), "Conducting the risk of terrorism: making the right decisions", *Reliability Engineering & System Safety*, Vol. 86, pp. 129-176.

Guimarees, A.C. and Ebecken, N. (1999), "Fuzzy FTA: A fuzzy fault tree system for uncertainty analysis", *Annals of Nuclear Energy*, Vol. 26, pp. 523-532.

Halebsky, M. (1989), "System safety design analysis technique applied on ship design", *Marine Technology*, Vol. 26, pp. 245-251.

Henley, J. and Kumamoto H. (1981), *Reliability engineering and risk assessment*, Prentice Hall, Englewood Clift, N J.

Henley, E.J. and Kumamoto, H. (1992), *Probabilistic risk assessment*, IEEE Press, USA.

Herrera, F.; Martinez, F. and Sanchez, P.J. (2005), "Managing non-homogeneous information in group decision making", *European Journal of Operational Research*, Vol. 166, pp. 115-132.

Hitt, M.A.; Middlemist, D.R. and Mathis R.L. (1989), *Management, Concepts and Effective Practice*, West Publishing Company, USA.

Hirsch, R.L.; Bezdek, R. and Wendling, R. (2005), "The inevitable peaking of world oil production", *Atlantic Council Bulletin*, Vol. 9, pp. 1-10.

HSE (1991), *Health and safety at work act 1974*, The Stationary Office Books, UK.

HSE (1995a), *Offshore installations (prevention of fire and explosion, and emergency response) on regulations 1995*, HSE Books, UK.

HSE (1995b), *A guide to offshore installations and pipeline works regulations 1995*, HSE Books, UK.

HSE (1996a), *A guide to pipeline safety regulations 1996*, HSE Books, UK.

HSE (1996b), *A guide to the installation verification and miscellaneous aspects of amendments by the offshore installation and well regulations 1996 to the offshore installations (safety case) regulations 1992*, HSE Books, UK.

HSE (1996c), *The offshore installations and wells (DCR regulations 1996)*, HSE books, UK.

Hsu, H.M. and Chen, T.C. (1994), "Aggregation of fuzzy opinion under group decision making", *Fuzzy Sets and Systems*, Vol. 79, pp. 279-285.

Huang, H.Z.; Tong, X. and Zuo, M. (2004), "Posbist fault tree analysis of coherent systems", *Reliability Engineering & System Safety*, Vol. 84, pp. 141-148.

Hwang, C.L. and Yoon, P. (1981), *Multiple attribute decision-making: methods and applications*, Springer- verlag, USA.

Jordaan, I. (2005), *Decisions under uncertainty - probabilistic analysis for engineering decisions*, Cambridge University Press, UK.

Kahneman, D.; Slovic, P. and Tversky, A. (1982), *Judgment under Uncertainty: Heuristics and Biases*, Cambridge University Press, Cambridge.

Kahraman, C.; Ulukan, Z. and Tolga, E. (1998), "A fuzzy weighted evaluation method using objective and subjective measures", *Proceedings of International ICSC Symposium on Engineering of Intelligent Systems (EIS'98)*, Vol. 1, University of La Laguna, Tenerife, pp. 57-63.

Kahraman, C.; Ufuk, C. and Ulukan, Z. (2003), "Multi-criteria supplier selection using fuzzy AHP", *Logistics Information Management*, Vol. 16, pp. 382-394.

Karwowski, W. and Mital, A. (1986), "Potential applications of fuzzy sets in industrial safety engineering", *Fuzzy Sets and Systems*, Vol. 19, pp. 105-120.

Khan, F.I.; Sadiq, R. and Husain, T. (2002), "Risk-based process safety assessment and control measures design for offshore process facilities", *Journal of Hazardous Materials*, Vol. 94, pp. 1-32.

Khan, F.I. and Haddara, M.M. (2003), "Risk-based maintenance: A quantitative approach for maintenance/inspection scheduling and planning", *Journal of Loss Prevention in the Process Industries*, Vol. 16, pp. 561-573.

Kim, S.H. and Ahn, B.S. (1997), "Group decision making procedure considering preference strength under incomplete information", *Computers and Operations Research*, Vol. 24, pp. 1101-1112.

Kim, S.H. and Ahn, B.S. (1999), "Interactive group decision making procedure under incomplete information", *European Journal of Operational Research*, Vol. 116, pp. 498-507.

Kim, S.H.; Choi, S. and Kim, J. (1999), "An interactive procedure for multiple attribute group decision making with incomplete information: range-based approach", *European Journal of Operational Research*, Vol. 118, pp. 139-152.

Kleiner, Y.; Sadiq, R. and Rajani, B. (2006a), "Modelling the deterioration of buried infrastructure as a fuzzy markov", *Journal of Water Supply Research and Technology: Aqua*, Vol. 55, pp. 67-80.

Kleiner, Y.; Sadiq, R. and Rajani, B. (2006b), "Failure Risk Management of Buried Infrastructure using Fuzzy-Based", *Journal of Water Supply Research and Technology: Aqua*, Vol. 55, pp. 81-94.

Klir, G.J. and Yuan, B. (1995), *Fuzzy sets and fuzzy logic: theory and applications*, Prentice Hall, Upper Saddle River, N.J.

Korta, J.P.; Lee, M.P.; Eisenberg, N. and Dewispelare, A. (1996), *Branch technical position on the use of expert elicitation in the high-level radioactive waste program*, U.S. Nuclear Regulatory Commission, NUREG-1563.

Krishnasamy, K. and Haddara, M. (2005), "Development of a Risk-Based Maintenance (RBM) Strategy for a Power-Generation Plant, *Journal of Loss Prevention in the Process Industries*, Vol. 18, pp. 69-81.

Kuo, C. (1998), *Managing shipping safety*, LLP, UK

Kuo, R.J.; Chi, S.C. and Kao, S.S. (2002), "A decision support system for selecting convenience store location through integration of fuzzy AHP and artificial neural network", *Computers in Industry*, Vol. 47, pp. 199-214.

Kwong, C.K. and Bai, H. (2003), "Determining the importance weights for the customer requirements in QFD using a fuzzy AHP with an extent analysis approach", *IIE Transactions*, Vol. 35, pp. 619-26.

Lahdelma, R.; Miettinen, R. and Salminen, K. (2005), "Reference point approach for multiple decision makers", *European Journal of Operational Research*, Vol. 164, pp. 785-791.

Lee, H.M. (1996), "Applying fuzzy set theory to evaluate the rate of aggregative risk in software development", *Fuzzy Sets and Systems*, Vol. 79, pp. 323-336.

Leung, L.C. and Cao, D. (2000), "On consistency and ranking of alternatives in fuzzy AHP", *European Journal of Operational Research*, Vol. 124, pp. 102-113.

Lewandowski, A. (1994), "Object-oriented modelling of natural gas pipeline network", *Proceeding of the 2nd object numeric conference*, Sunriver, Oregon, 1994.

Li, D.F. (2007), "A fuzzy closeness approach to fuzzy multi-attribute decision making", *Fuzzy Optimization and Decision Making*, Vol. 6, pp. 237-254.

Li, D.F. and Yang, J.B. (2004), "Fuzzy linear programming technique for multi-attribute group decision making in fuzzy environments", *Information Sciences*, Vol. 158, pp. 263-275.

Liang, G.S. and Wang, M.J. (1993), "Fuzzy fault-tree analysis using failure possibility", *Microelectronics and Reliability*, Vol. 33, pp. 583-597.

Lin, T.C. and Wang, M.J. (1998), "Hybrid fault tree analysis using fuzzy sets", *Reliability Engineering and System Safety*, Vol. 58, pp. 205-231.

Lin, T.C. and Wang, M.J. (1998), "Hybrid fault tree analysis using fuzzy sets", *Reliability Engineering & System Safety*, Vol. 58, pp. 205-231.

Liu, D. and Stewart, T.J. (2003), "Integrated object-oriented framework for MCDM and DSS modelling", *Decision Support Systems*, Vol. 38, pp. 421-434.

Lopez de Mantaras, L. (1990); *Aproximate Reasoning Models.* Ellis Horwood Series in Artificial Intelligence, 1990, U.K.

Makridakis, S.; Wheelwright, S. and McGee, E. (1983), *Forecasting: methods and applications*, Wiley, USA.

Mandke, J. S. (1990), "Corrosion causes most pipeline failures in Gulf of Mexico", *Oil and Gas Journal*, Vol. 8, pp. 40-44.

Marakas, G.M. (2003), *Decision Support Systems in the 21st Century,* Prentice hall, USA.

Martin, J. and Odell, J.J. (1994), *Object-Oriented Methods: A Foundation,* 1st Ed, PTR Prentice Hall.

Mather, A. (1995) *Offshore engineering: An Introduction,* 1st Ed, Witherby & Co Ltd.

Matsinos, Y.G.; Deangelis, D.L. and Wolff, W. (1994), "Using an object-oriented model for ecological risk assessment on a great blue heron colony", *Math. Comput. Modelling,* Vol. 20, pp. 75-82

McKinney, D.C. and Cai, X. (2002), Linking GIS and water resources management models: An object-oriented method, *Environmental Modelling & Software,* Vol. 33, pp. 413-425.

Mikhailov, L. (2004), "A fuzzy approach to delivering priorities from interval pairwise comparison judgments", *European Journal of Operational Research,* Vol. 159, pp. 687-707.

Military Standard (1993), "System Safety Program Requirements", MIL-STD-882C, January, AMSC Number F6861.

Military standard (1999), *Department of defence; military standard; system safety program requirements, MIL-STD-882D,* USA.

Miller, G.A. (1956), "The magical number seven plus or minus two: some limit on our capacity for processing information", *The Psychological Review,* Vol. 63, pp. 81-97.

Misra, K.B. and Weber, G.G. (1990), "Use of fuzzy set theory for level-I studies in probabilistic risk assessment", *Fuzzy Sets and Systems,* Vol. 37, pp. 139-160.

Modarres, M. (2006), *Risk analysis in engineering: probabilistic techniques,* Tools and Trends, CRC, USA.

Mon, D.L.; Cheng, C.H. and Lin, J.C. (1994) "Evaluating weapon system using fuzzy analytic hierarchy process based on entropy weight". *Fuzzy Sets and System,* Vol. 62, pp. 127-134.

Murphy, P.J.; Bevans, K. and Layton, B. (1999), *Criterium decision plus, incl. a tutorial*, InfoHarvest, USA.

NOPSA (2004), *National offshore petroleum safety authority transitional plan*, available at
(Dec 10,2004), (http://www.nopsa.gov.au/downloads/Transitional_Plan.pdf).

NORSOK D-010. (2004), *Well integrity in drilling and well operations. Rev. 3.*

NRC (1985), *Oil in the sea-inputs, fates, and effects*, National Academy Press, USA.

Norris, J.R. (1998), *Markov chains, statistical and probabilistic mathematics: Series 2*, Cambridge university press, UK.

NTSB (1990), *Pipeline accident report*, Report PB90-916502 NTSB/ PAR-90/02, USA.

OEA (2001), *Vulnerability assessment and survey program*, U.S Department of Energy Office of Energy Assurance, available at (Aug 20, 2007),

(www.esisac.com/publicdocs/assessment_methods/OEA_VA_Lessons_Learned_Best_Practices.pdf).

Olcer, A.I. and Odabasi, A.Y. (2005), "A new fuzzy multiple attributive group decision making methodology and its application to propulsion/manoeuvring system selection problem", *European Journal of Operational Research*, Vol.166, pp. 93-114.

Onisawa, T. and Nishiwaki, Y. (1988), "Fuzzy human reliability on the CHERNOBYL accident", *Fuzzy Sets and Systems*. Vol. 28, pp. 115-127.

Onisawa, T. (1988), "An approach to human reliability in man-machine systems using error possibility", *Fuzzy Sets and Systems*, Vol. 27, pp. 87-103.

Onisawa, T. (1990), "An application of fuzzy concepts to modelling of reliability analysis", *Fuzzy Sets and Systems*, Vol. 37, pp. 266-286.

Onisawa, T. (1996), "Subjective analysis of system reliability and its analyzer", *Fuzzy Sets and Systems*, Vol. 83, pp. 249-269.

Pan, N. and Wang, H. (2007), "Assessing failure of bridge construction using fuzzy fault tree analysis", *4th International Conference on Fuzzy System and Knowledge Discovery*, Vol. 1, pp. 96-100.

Papadakis, G. (2000), "Assessment of Requirement on Safety Management System in EU Regulations for Control Major Hazard Pipelines", *Journal of Hazardous Materials*, Vol. 78, pp. 63-89.

Parfomak, W.P. (2007), *Pipeline safety and security: federal programs*, 110TH Congressional research service, CRS order code RL33347.

Park, K.S. and Kim, S.H. (1997), "Tools for interactive multi-attribute decision making with incompletely identified information", *European Journal of Operational Research*, Vol. 98, pp. 111-123.

Park, K.S.; Kim, S.H and Yoon, Y.C. (1996), "Establishing strict dominance between alternatives with special type of incomplete information", *European Journal of Operational Research*, Vol. 96, pp. 398-406.

Park, K.S. (2004), "Mathematical programming models for characterizing dominance and potential optimality when multi-criteria alternative values and weights are simultaneously incomplete", *IEEE Transactions on Systems, Man, and Cybernetics*, Vol. 34, pp. 601-614.

Parkan, A. (1994), "Decision making under partial probability information", *European Journal of Operational Research*, Vol. 79, pp. 115–122.

Pillay, A. and Wang, J. (2003), *Technology and safety of marine systems*, Elsevier Science Publisher, UK.

Ping, H.; Zhang, H. and Zuo, M.J. (2007), "Fault tree analysis based on fuzzy logic", *Annual Reliability and Maintainability Symposium*, pp. 77-82.

Power, D.J. (2002), *Decision support systems, concepts and resources for managers*, Quorum Books, USA.

Preyssl, C. (1995), "Safety risk assessment and management - the ESA approach", *Reliability Engineering & System Safety,* Vol. 49, pp. 303–309.

PSA. (2002), *The risk level on the norwegian continental Shelf* (In Norwegain - Risikonivå pånorsk sokkel), Petroleum Safety Authority (PSA), Stavanger, Norway.

Ramanathan, R. and Ganesh, R.S. (1994), "Group preference aggregation methods employed in AHP: an evaluation and an intrinsic process for deriving members' weightages", *European Journal of Operational Research,* Vol. 79, pp. 249-265.

Rausand, M. and Hoyland, A. (2004), *System reliability theory: models, statistical methods and applications*, John Wiley and Son, Inc, New Jersey, USA.

Roberge, P.R. (1996), "An object oriented model of material failures", *Computers in Industry*, Vol. 31, pp. 85-93.

Ross, T.J.; Wagner, R. and Luger, G. (1992), "Object-oriented programming for scientific codes", *Journal of Computing in Civil engineering,* Vol. 6, pp. 497-514.

Ruoning, X. and Xiaoyan, Z. (1992), "Extensions of the AHP in fuzzy environment", *Fuzzy Sets and Systems*, Vol. 52, pp. 251-257.

Saaty, T.L. (1990), *Analytical hierarchy process*, RWS publications, Pittsburgh.

Saaty, T.L. (2001), How to Make a Decision? In T.L. Saaty & L.G. Vargas (Eds), *Models, Methods, Concepts and Applications of the Analytic Hierarchy Process.* Dordechet, MA: Kluwer International Series.

Sadiq, R.; Kleiner, Y. and Rajani, B. (2004), "Aggregative risk analysis for water quality failure in distribution networks", *Aqua-Journal of Water Supply: Research and Technology*, Vol. 53, pp. 241-261.

Sadiq, R. and Husain, T. (2005), "A fuzzy-based methodology for an aggregative environmental risk assessment: a case study of drilling waste", *Environmental Modelling & Softwares,* Vol. 20, pp. 33-46.

Sahoo, P.K. and Dutta, D. (2008), "Fuzzy decision aid for technology evaluation", *Defence Science Journal,* Vol. 58, pp. 103-119.

Salo, A.A. (1995), "Interactive decision aiding for group decision support", *European Journal of Operational Research,* Vol. 84, pp. 134-149.

Sawer, J.P. and Rao, S.S. (1994), "Fault tree analysis of fuzzy mechanical systems", *Microelectronic Reliability,* Vol. 34, pp. 653-667.

Sentz, K. and Ferson, S. (2002), *Combination of evidence in Dempster-Shafer theory,* SANDIA Tech. Report, SAND2002-0835, 96 pages.

Shafer, G. (1976), *A mathematical theory of evidence,* Princeton University Press, Princeton.

Shiha, H.S.; Shyur, H.J. and Stanley, L.E. (2007), "An extension of TOPSIS for group decision making", *Mathematical and Computer Modeling,* Vol. 45, pp. 801-813.

Shu, M.H.; Cheng, C.H. and Chang, J.R. (2006), "Using intuitionistic fuzzy fault-tree analysis on printed circuit board assembly", *Microelectronics Reliability,* Vol. 46, pp. 2139-2146.

Simon, H. (1982), *The Sciences of the artificial,* 2nd Ed, MIT Press.

Singer, D. (1990), "A fuzzy set approach to fault tree and reliability analysis", *Fuzzy Sets and Systems,* Vol. 34, pp. 145-155.

SKB (1999), TR 99-09, *Data Uncertainties.*

Solomatine, D.P. (1996), "Object orientation in hydraulic modeling architectures", *Journal of Computing in Civil Engineering,* Vol. 10, pp. 125-35.

Spouge, J. (1999), *A guide to quantitative risk assessment for offshore installation,* CMPT publications, Abrdeen, UK.

Sugeno, M. (1999), *Fuzzy modelling and control,* CRC Press, Florida, USA.

Suresh, P.V.; Babar, A.K. and Venkat Raj, V. (1996), "Uncertainty in fault tree analysis: a fuzzy approach", *Fuzzy sets and systems,* Vol. 83, pp. 135-141.

Tanaka, H.; Fan, L., Lai, S. and Toguchi, K. (1983), "Fault tree analysis by fuzzy probability", *IEEE Transactions on Reliability,* Vol. 32, pp. 453-457.

Tang, M.T.; Tzeng, G.H. and Wang, S.W. (2000), "A hierarchy fuzzy MCDM method for studying electronic marketing strategies in the information service industry", *Journal of International Information Management,* Vol. 8, pp. 1-22.

Teodorovic, D. (1985), "Multi-criteria ranking of air shuttle alternatives", *Transportation Research Part B: Methodological,* Vol. 19, pp. 63-72.

Tummala, V.M.R. and Leung, Y.H. (1995), "A risk management model to assess safety and reliability risks", *International Journal of Quality and Reliability Management,* Vol. 13, pp. 53-62.

UKOOA (1999), *Guidelines on a framework for risk related decision making,* Offshore Operators Association, UK.

Van Laarhoven, P.J.M. and Pedrycz, W. (1983), "A fuzzy extension of saaty's priority theory", *Fuzzy Sets and Systems,* Vol. 11, pp. 229-241.

Vinnem, J.E. (2000), *Offshore risk assessment: Principle, modelling and application of quantitative risk assessment,* Springer, London.

Wang, J. (2002), "Offshore safety case approach and formal safety assessment of ships", *Journal of Safety Research,* Vol. 33, pp. 81-115.

Wang, J. (2002a), "A brief review of marine and offshore safety assessment", *Marine Technology,* Vol. 39, pp. 77-85.

Wang, J. and Ruxton, T. (1998), "A design for safety methodology of large engineering system", *Journal of Engineering Design,* Vol. 9, pp. 159-170.

Wang, J.; Sii, H.S.; Yang, J.B; Pillay, A.; Yu, D.; Liu, J.; Maistralis, E. and Saajedi, A. (2004), "Use of advances in technology for maritime risk assessment", *Risk Analysis*, Vol. 24, pp. 1041-1063.

Wang, J.; Yang, J.B. and Sen, P. (1995), "Safety analysis and synthesis using fuzzy sets and evidential reasoning", *Reliability Engineering & System Safety*, Vol. 47- pp. 103-118.

Wang, Y. and Elhag, T. (2007), "A fuzzy group decision making approach for bridge risk assessment", *Computers and Industrial Engineering*, Vol. 53, pp. 137-148.

Weber, M. (1987), "Decision making with incomplete information", *European Journal of Operational Research*, Vol. 28, pp. 44-57.

Weber, P. and Jouffe, L. (2006), "Complex systems reliability modelling with dynamic object-oriented bayesian networks (DOOBN)", *Reliability Engineering & System Safety*, Vol. 91, pp. 149-162.

Woodson, R. D. (1991), *A critical review of offshore pipeline failures*, National Research Council (NRC), USA.

Wyss, G.D. and Durán, F.A. (2002), "Object-based approaches to risk and reliability analysis: OBEST methodology and applications", *Proceedings of the 6th International Conference on Probabilistic Safety Assessment and Management*, San Juan, Puerto Rico, USA.

Wyss, G.D.; Duran, F.A. and Danini, V.J. (2004), "An object-oriented approach to risk and reliability analysis: Methodology and aviation safety applications", *Simulation*, Vol. 80, pp. 33-43.

Xu, Z. (2000), "On consistency of the weighted geometric mean complex judgment matrix in AHP", *European Journal of Operational Research*, Vol. 126, pp. 683-687.

Yager, R.R. (1980), "On a general class of fuzzy connectives". *Fuzzy Sets and Systems*, Vol. 4, pp. 235–242.

Yager, R.R. (2004), "On the determination of strength of belief for decision support under uncertainty – Part 2: fusing strengths of belief", *Fuzzy Sets and Systems,* Vol. 142, pp. 129-142.

Yang, Z. (2006), *Risk assessment and decision making of container supply chains*, PhD Thesis, School of Engineering, Liverpool John Moores University, UK.

Yang, J.B. and Xu, D.L. (2002), "On the evidential reasoning algorithm for multiple attribute decision analysis under uncertainty", *IEEE Transactions on Systems, Man and Cybernetics – Part A: Systems and Humans*, Vol. 32, pp. 289-304.

Yeh, C.H. (2002), "A problem-based selection of multi-attribute decision-making methods", *International Transactions in Operational Research*, Vol. 9, pp. 169-181.

Yong, D. (2006), "Plant location selection based on fuzzy TOPSIS", *International Journal of Advanced Manufacturing Technology,* Vol. 28, pp. 839-844.

Zadeh, L.A. (1965), "Fuzzy sets", *Information and Control*, Vol. 8, pp. 338-353.

Zadeh, L.A., (1984), "Review of books: A mathematical theory of evidence", *AI Magazine*, Vol. 5, pp. 81-83.

Zanakis, S.H.; Solomon, A.; Wishart, N. and Dublish, S. (1998), "Multi-attribute decision making: A simulation comparison of select methods", *European Journal of Operational Research,* Vol. 107, pp. 507-529.

Zhao, R. and Govind, R. (1991), "Defuzzification of fuzzy intervals", *Fuzzy Sets and Systems*, Vol. 43, pp. 45-50.

Zimmerman, H.J. (1991), *Fuzzy set theory and its applications* (2nd edition), Kluwer Academic Publishers.

Zimmermann, H.J. and Zysno, P. (1985), "Quantifying vagueness in decision models", *European Journal of Operational Research*, Vol. 22, pp. 148-158.

Appendices

Appendix 1

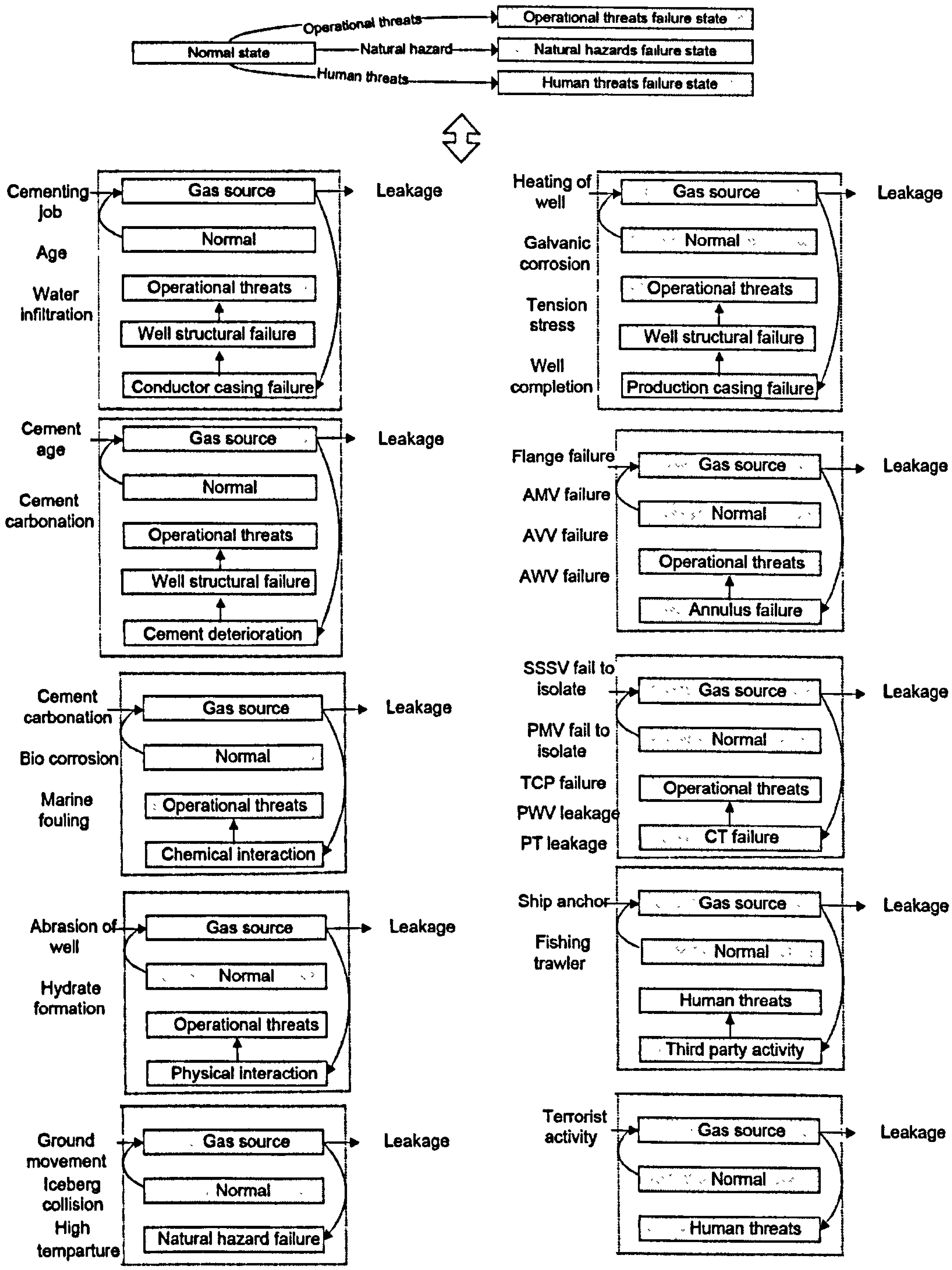


Figure A1.1 State transition of gas wells

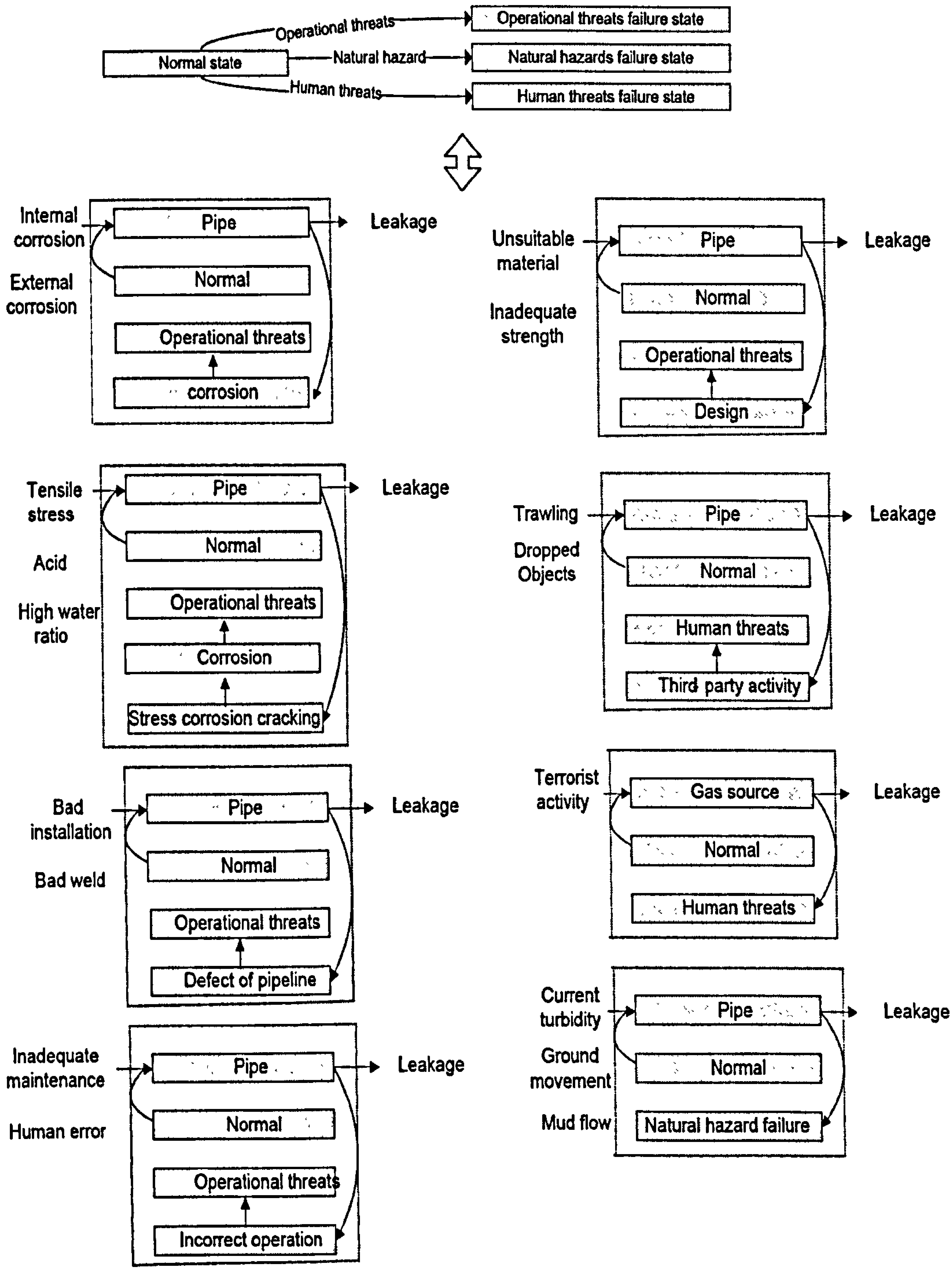


Figure A1.2 State transition of gas pipelines

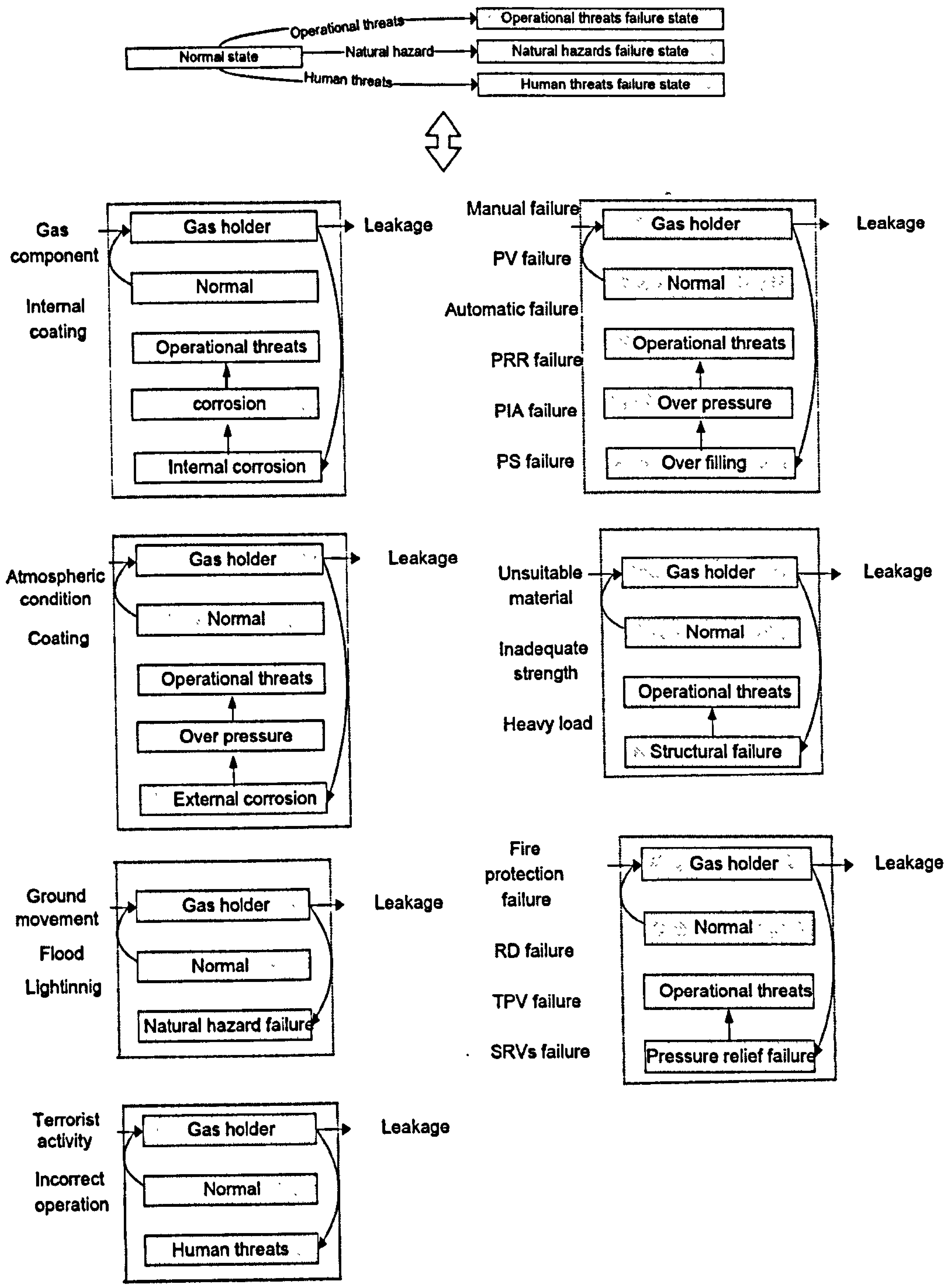


Figure A1.3 State transition of gas holders

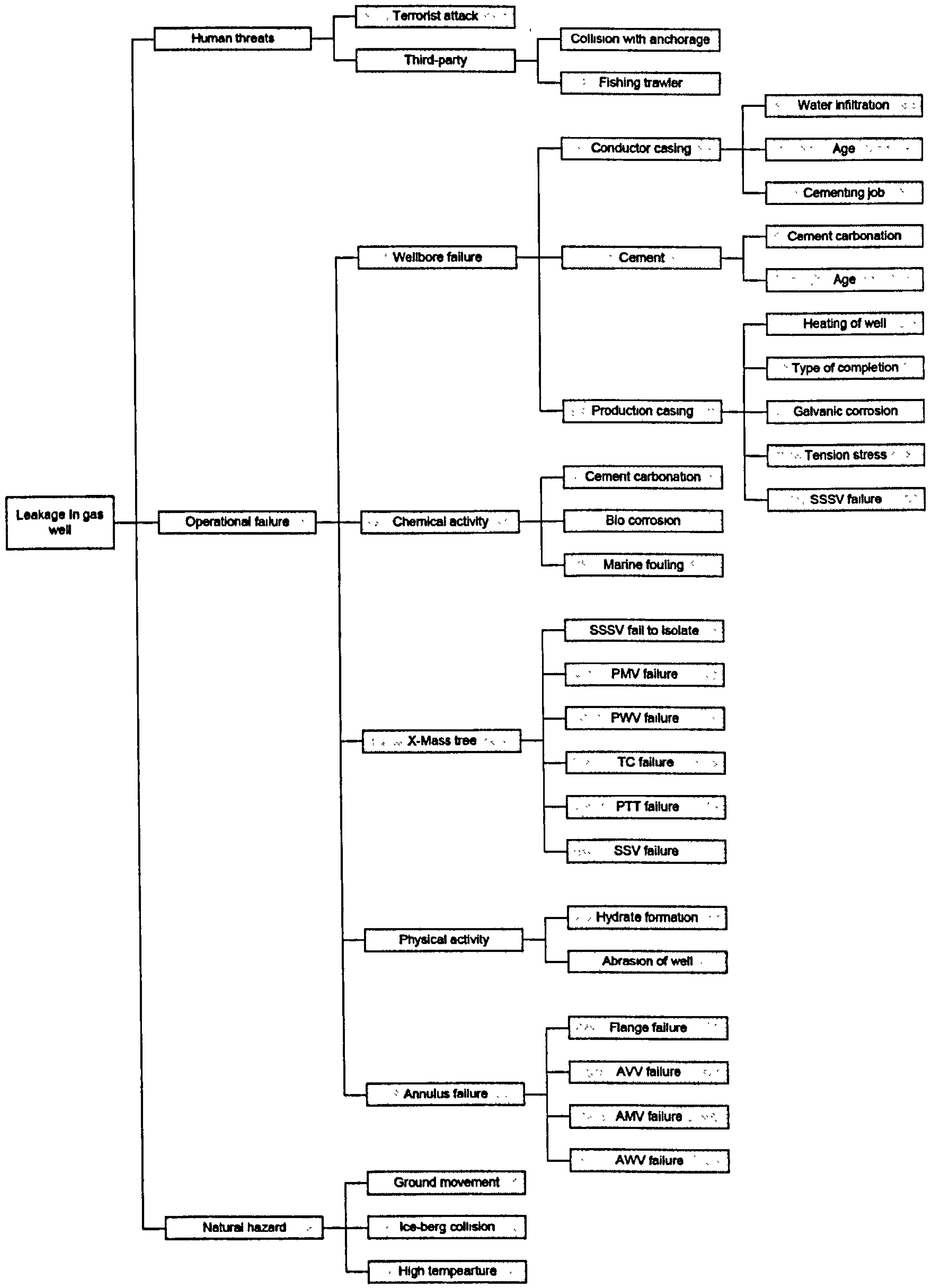


Figure A1.4 Framework of aggregative risk assessment of gas wells

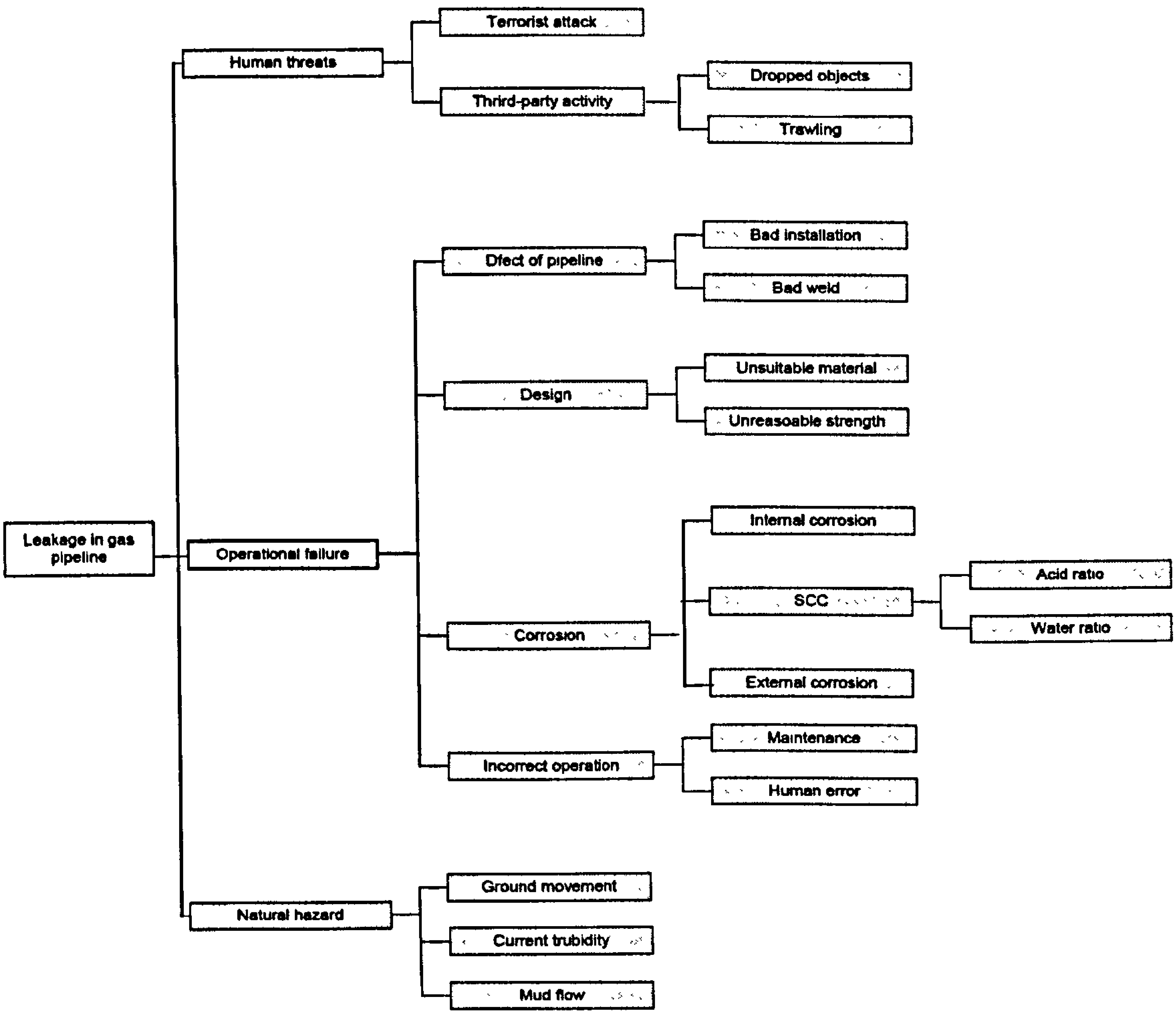


Figure A1.5 Frameworks of aggregative risk assessment of gas pipelines

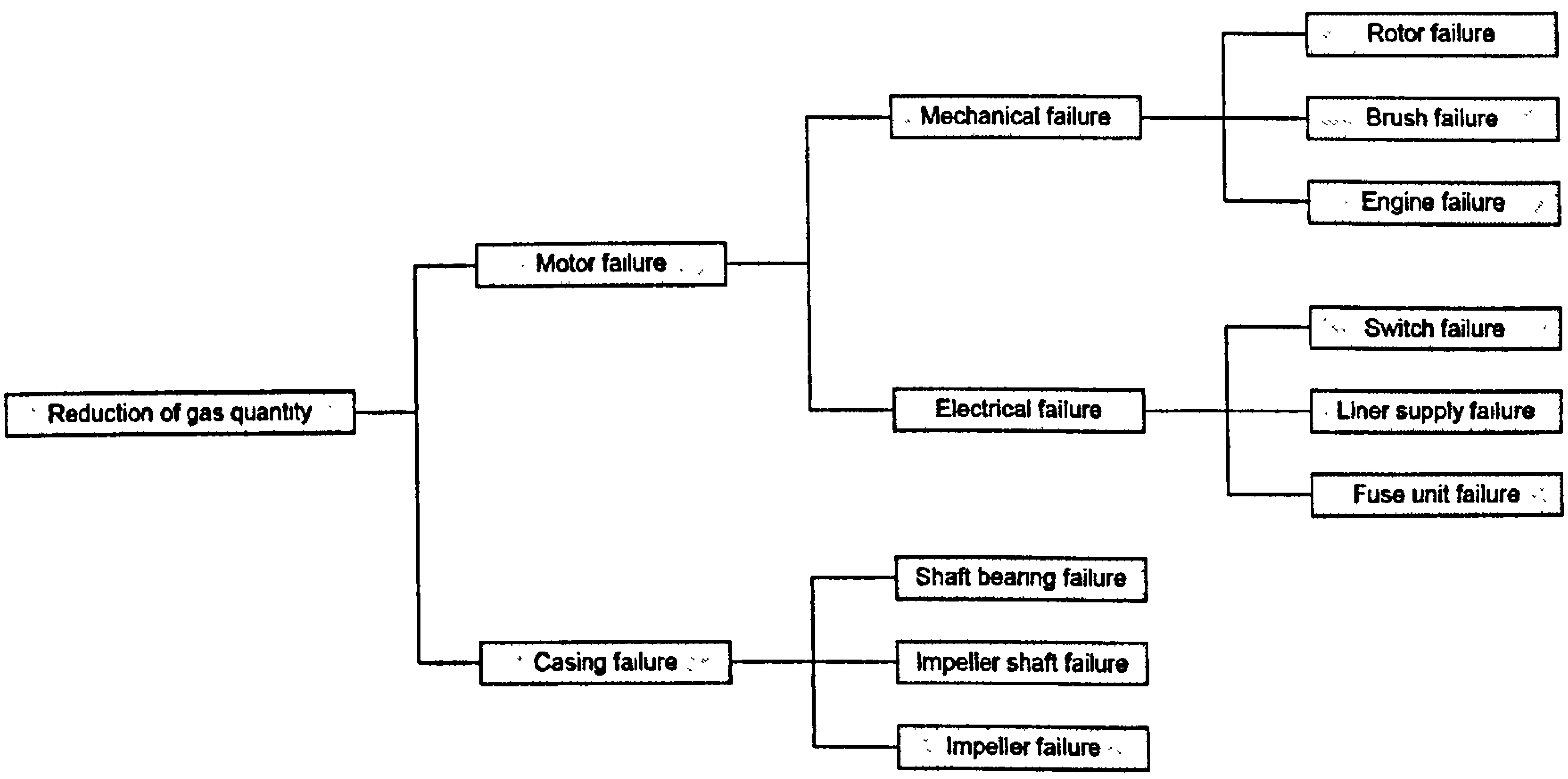


Figure A1.6 Framework of risk assessment of reduce gas quantity in compressors

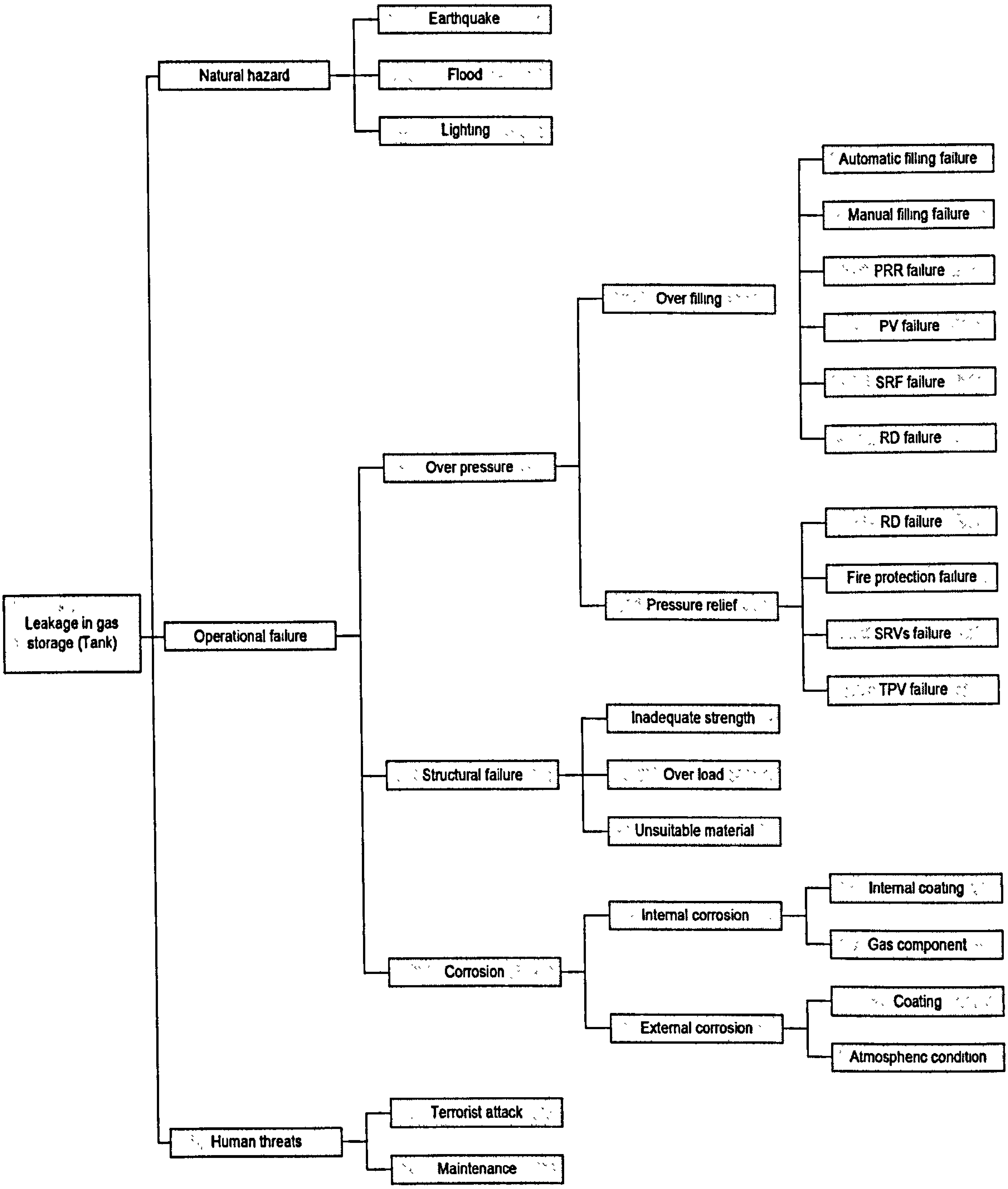


Figure A1.7 Frameworks of aggregative risk assessment of gas holders

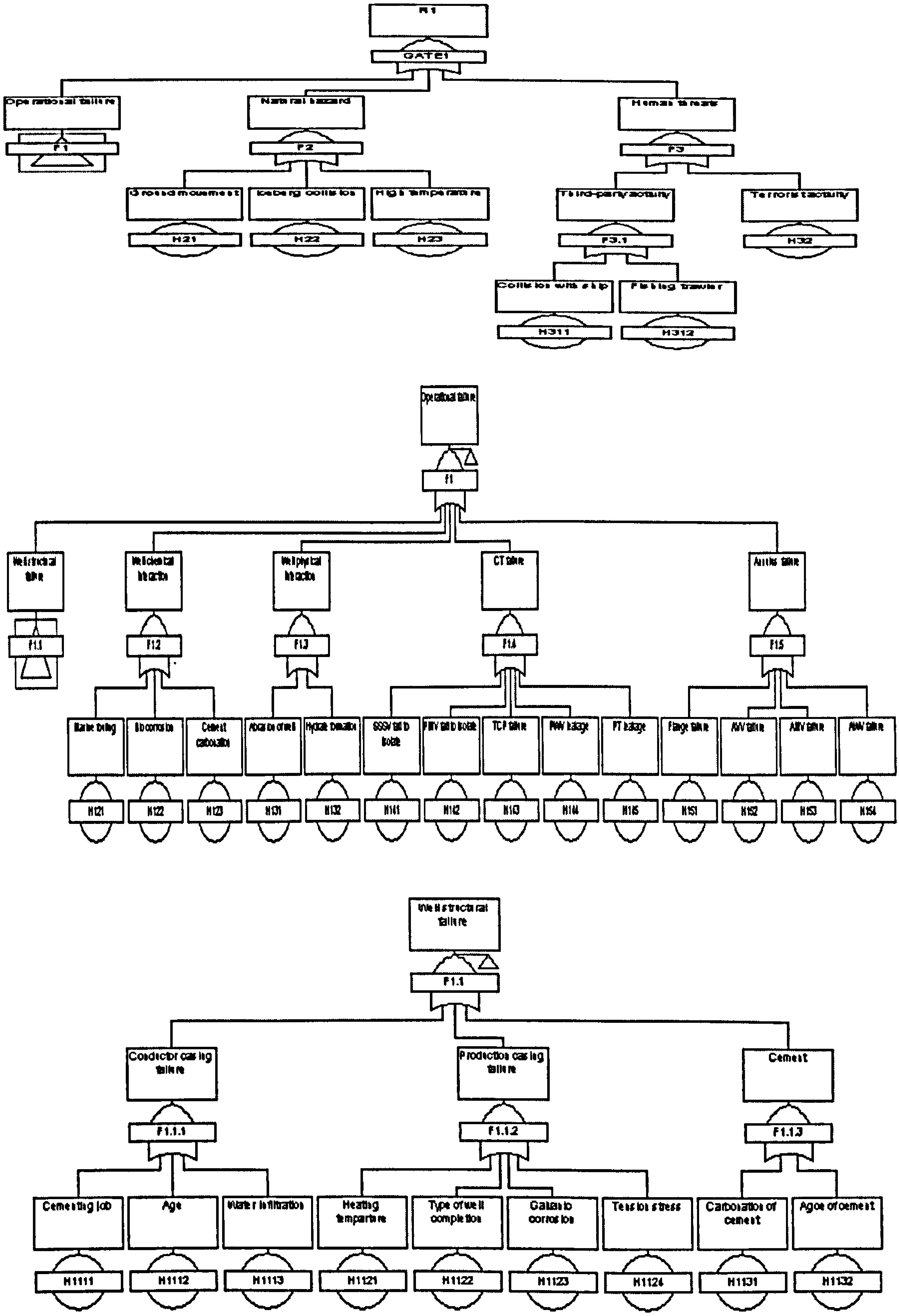


Figure A1.8 Fault tree of gas wells

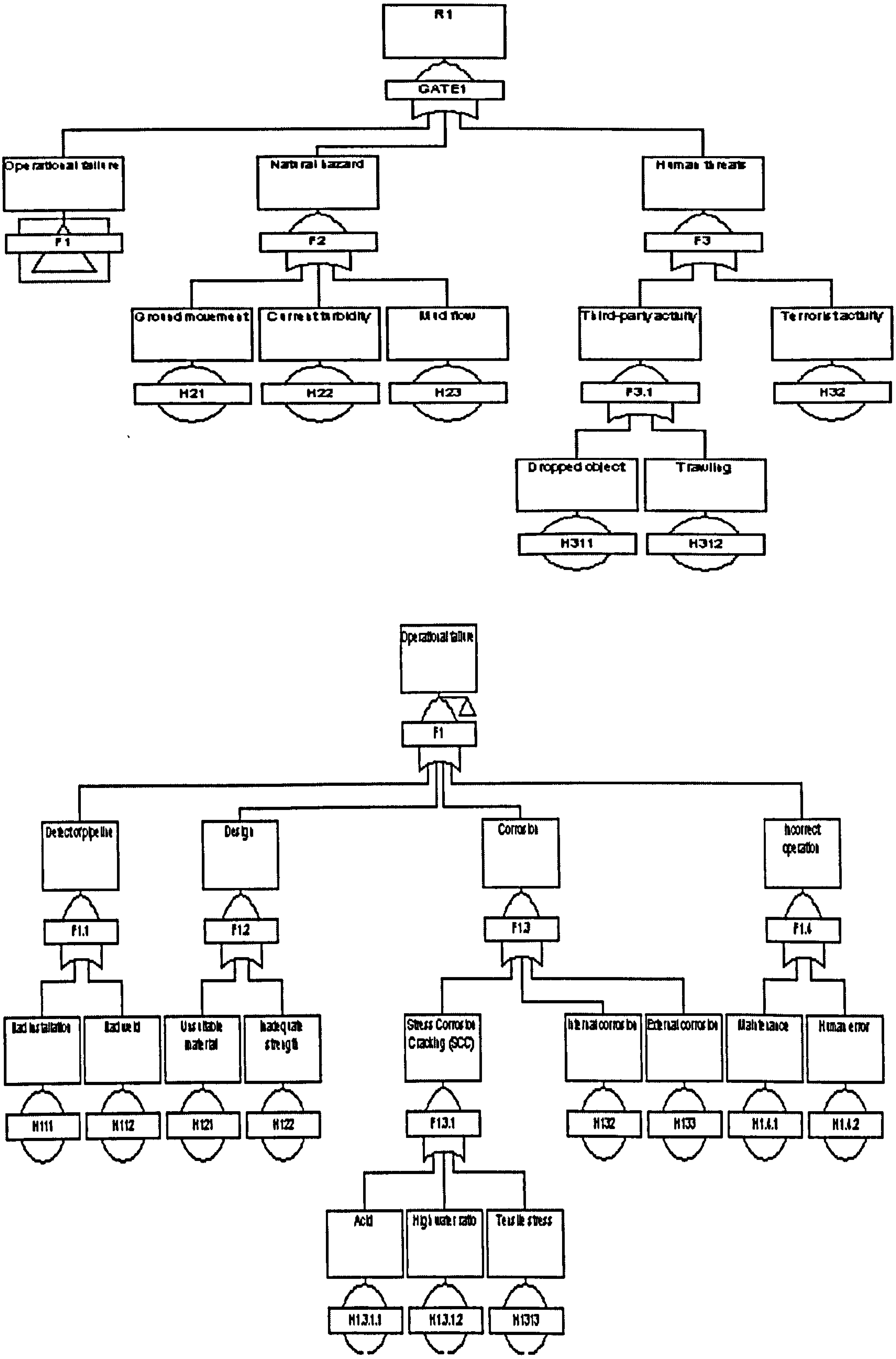


Figure A1.9 Fault tree of gas pipelines

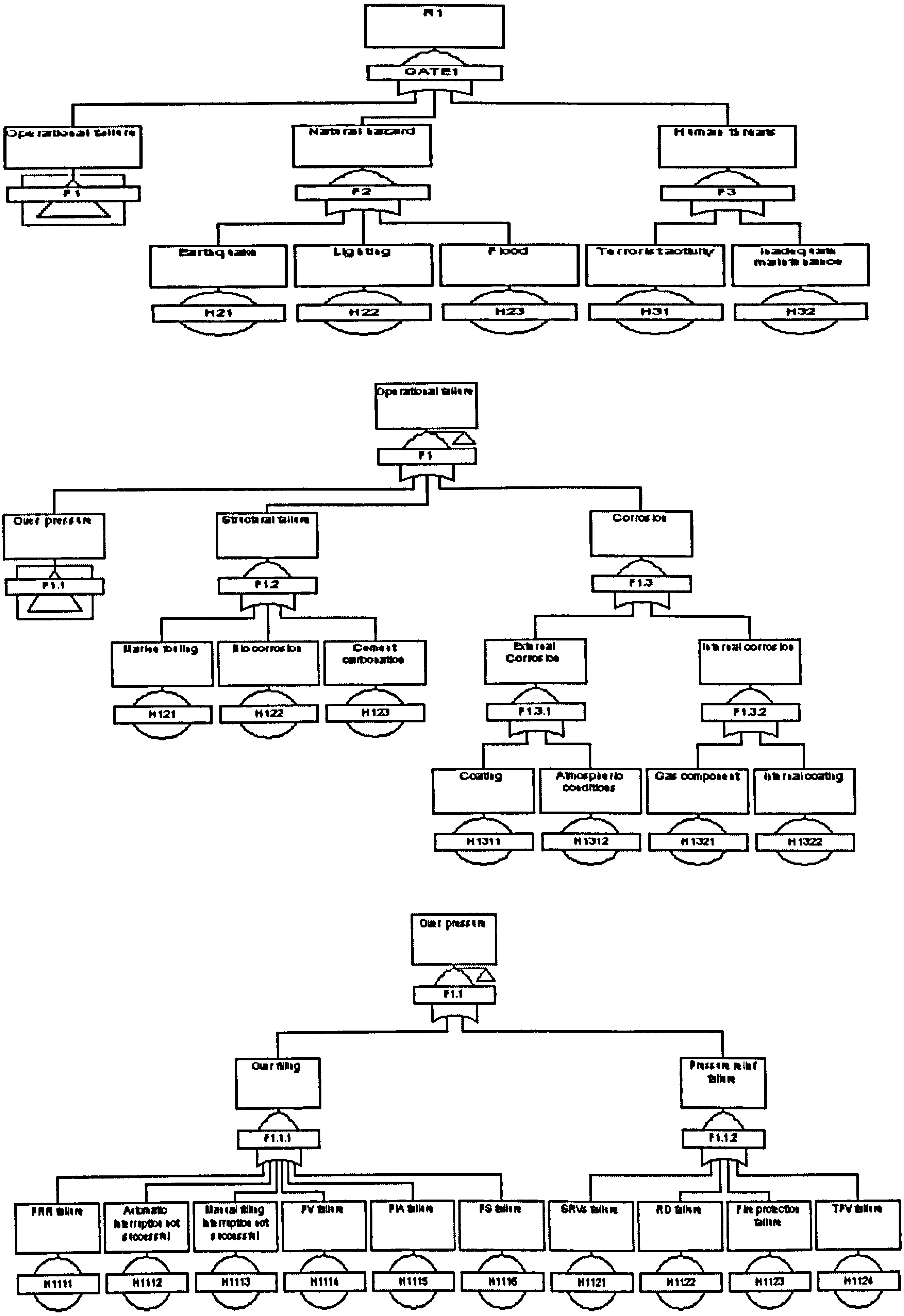


Figure A1.10 Fault tree of gas holders

Appendix 2

Table A2.1 Structure model of leakage in gas wells

FAR	Attributes in level-1	Attributes in level-2	Attributes in level-3	Attributes in level-4	Weights of attributes in level-1	Weights of attributes in level-2	Weights of attributes in level-3	Weights of attribute in level-4	Grade L	Grade S
$X^1_{0,1}$										
	$X^2_{1,1}$	$X^3_{1,1}$	$X^4_{1,1}$	$X^{5*}_{1,1}$	$w^2_{1,1}$	$w^3_{1,1}$	$w^4_{1,1}$	$w^{5*}_{1,1}$	2	4
				$X^{5*}_{1,2}$				$w^{5*}_{1,2}$	3	2
				$X^{5*}_{1,3}$				$w^{5*}_{1,3}$	1	3
			$X^4_{1,2}$	$X^{5*}_{2,1}$			$w^4_{1,2}$	$w^{5*}_{2,1}$	2	4
				$X^{5*}_{2,2}$				$w^{5*}_{2,2}$	1	3
				$X^{5*}_{2,3}$				$w^{5*}_{2,3}$	4	3
				$X^{5*}_{2,4}$				$w^{5*}_{2,4}$	1	3
			$X^4_{1,3}$	$X^{5*}_{3,1}$			$w^4_{1,3}$	$w^{5*}_{3,1}$	1	4
				$X^{5*}_{3,2}$				$w^{5*}_{3,2}$	2	3
		$X^3_{1,2}$	$X^{4*}_{2,1}$			$w^3_{1,2}$	$w^{4*}_{2,1}$		1	2
			$X^{4*}_{2,2}$				$w^{4*}_{2,2}$		3	3
			$X^{4*}_{2,3}$				$w^{4*}_{2,3}$		1	4
		$X^3_{1,3}$	$X^{4*}_{3,1}$			$w^3_{1,3}$	$w^{4*}_{3,1}$		2	3
			$X^{4*}_{3,2}$				$w^{4*}_{3,2}$		1	2
		$X^3_{1,4}$	$X^{4*}_{4,1}$			$w^3_{1,4}$	$w^{4*}_{4,1}$		2	4
			$X^{4*}_{4,2}$				$w^{4*}_{4,2}$		3	3
			$X^{4*}_{4,3}$				$w^{4*}_{4,3}$		1	3
			$X^{4*}_{4,4}$				$w^{4*}_{4,4}$		3	2
			$X^{4*}_{4,5}$				$w^{4*}_{4,5}$		3	1

		$X_{1,5}^{3}$	$X_{5,1}^{4*}$			$w_{1,5}^{3}$	$w_{5,1}^{4*}$		4	2
			$X_{5,2}^{4*}$				$w_{5,2}^{4*}$		3	1
			$X_{5,3}^{4*}$				$w_{5,3}^{4*}$		3	1
			$X_{5,4}^{4*}$				$w_{5,4}^{4*}$		3	1
	$X_{1,2}^{2}$	$X_{2,1}^{3*}$			$w_{1,2}^{2}$	$w_{2,1}^{3*}$			2	5
		$X_{2,2}^{3*}$				$w_{2,2}^{3*}$			1	4
		$X_{2,3}^{3*}$				$w_{2,3}^{3*}$			3	3
	$X_{1,3}^{2}$	$X_{3,1}^{3}$	$X_{1,1}^{4*}$		$w_{1,3}^{2}$	$w_{3,1}^{3}$	$w_{1,1}^{4*}$		2	4
			$X_{1,2}^{4*}$				$w_{1,2}^{4*}$		2	5
		$X_{3,2}^{3*}$				$w_{3,2}^{3*}$			1	5

Table A2.2 Structure model of leakage in pipelines

FAR	Attributes in level-1	Attributes in level-2	Attributes in level-3	Attributes in level-4	Weight s of attributes in level-1	Weights of attributes in level-2	Weights of attributes in level-3	Weights of attribute in level-4	Grade L	Grade S
$X^1_{0,1}$										
	$X^2_{1,1}$	$X^3_{1,1}$	$X^{4*}_{1,1}$		$w^2_{1,1}$	$w^3_{1,1}$	$w^{4*}_{1,1}$		3	3
			$X^{4*}_{1,2}$				$w^{4*}_{1,2}$		2	3
		$X^3_{1,2}$	$X^{4*}_{2,1}$			$w^3_{1,2}$	$w^{4*}_{2,1}$		1	3
			$X^{4*}_{2,2}$				$w^{4*}_{2,2}$		1	4
		$X^3_{1,3}$	$X^{4*}_{3,1}$			$w^3_{1,3}$	$w^{4*}_{3,1}$		2	3
			$X^{4*}_{3,2}$				$w^{4*}_{3,2}$		2	3
			$X^4_{3,3}$	$X^{5*}_{3,1}$			$w^4_{3,3}$	$w^{5*}_{3,1}$	3	3
				$X^{5*}_{3,2}$				$w^{5*}_{3,2}$	2	4
				$X^{5*}_{3,3}$				$w^{5*}_{3,3}$	2	3
		$X^3_{1,4}$	$X^{4*}_{4,1}$			$w^3_{1,4}$	$w^{4*}_{4,1}$		2	2
			$X^{4*}_{4,2}$				$w^{4*}_{4,2}$		3	4
	$X^2_{1,2}$	$X^{3*}_{2,1}$			$w^2_{1,2}$	$w^{3*}_{2,1}$			1	5
		$X^{3*}_{2,2}$				$w^{3*}_{2,2}$			2	5
		$X^{3*}_{2,3}$				$w^{3*}_{2,3}$			3	5
	$X^2_{1,3}$	$X^3_{3,1}$	$X^{4*}_{1,1}$		$w^2_{1,3}$	$w^3_{3,1}$	$w^{4*}_{1,1}$		3	5
			$X^{4*}_{1,2}$				$w^{4*}_{1,2}$		3	5
		$X^{3*}_{3,2}$				$w^{3*}_{3,2}$			1	4

Table A2.3 Structure model of leakage in gas holders

FAR	Attributes in level-1	Attributes in level-2	Attributes in level-3	Attributes in level-4	Weight of attributes in level-1	Weight of attributes in level-2	Weight of attributes in level-3	Weight of attribute in level-4	Grade L	Grade S
$X^1_{0,1}$										
	$X^2_{1,1}$	$X^3_{1,1}$	$X^4_{1,1}$	$X^{5*}_{1,1}$	$w^2_{1,1}$	$w^3_{1,1}$	$w^4_{1,1}$	$w^{5*}_{1,1}$	1	4
				$X^{5*}_{1,2}$				$w^{5*}_{1,2}$	1	5
				$X^{5*}_{1,3}$				$w^{5*}_{1,3}$	3	3
				$X^{5*}_{1,4}$				$w^{5*}_{1,4}$	1	4
				$X^{5*}_{1,5}$				$w^{5*}_{1,5}$	2	5
				$X^{5*}_{1,6}$				$w^{5*}_{1,6}$	2	2
			$X^4_{1,2}$	$X^{5*}_{2,1}$			$w^4_{1,2}$	$w^{5*}_{2,1}$	1	3
				$X^{5*}_{2,2}$				$w^{5*}_{2,2}$	1	4
				$X^{5*}_{2,3}$				$w^{5*}_{2,3}$	2	4
				$X^{5*}_{2,4}$				$w^{5*}_{2,4}$	1	2
		$X^3_{1,2}$	$X^{4*}_{2,1}$			$w^3_{1,2}$	$w^{4*}_{2,1}$		2	3
			$X^{4*}_{2,2}$				$w^{4*}_{2,2}$		1	4
			$X^{4*}_{2,3}$				$w^{4*}_{2,3}$		3	3
		$X^3_{1,3}$	$X^4_{3,1}$	$X^{5*}_{1,1}$		$w^3_{1,3}$	$w^4_{3,1}$	$w^{5*}_{1,1}$	2	2
				$X^{5*}_{1,2}$				$w^{5*}_{1,2}$	1	3
			$X^4_{3,2}$	$X^{5*}_{2,1}$			$w^4_{3,2}$	$w^{5*}_{2,1}$	1	2
				$X^{5*}_{2,2}$				$w^{5*}_{2,2}$	2	2
	$X^2_{1,2}$	$X^{3*}_{2,1}$			$w^2_{1,2}$	$w^{3*}_{2,1}$			1	5
		$X^{3*}_{2,2}$				$w^{3*}_{2,2}$			1	5
		$X^{3*}_{2,3}$				$w^{3*}_{2,3}$			2	3

	$X_{1,3}^{2}$	$X_{3,1}^{3*}$			$w_{1,3}^{2}$	$w_{3,1}^{3*}$			1	5
		$X_{3,2}^{3*}$				$w_{3,2}^{3*}$			2	3

Table A2.4 BRIs of gas wells

X_{ij}^{*}	$TPFN_L$				$TPFN_S$				$TPFN_{LS}$			
$X_{3,2}^{3*}$	0	0	0.1	0.2	0.8	0.9	1	1	0.00	0.00	0.10	0.20
$X_{1,1}^{4*}$	0.1	0.25	0.25	0.4	0.6	0.75	0.75	0.9	0.06	0.19	0.19	0.36
$X_{1,2}^{4*}$	0.1	0.25	0.25	0.4	0.8	0.9	1	1	0.08	0.23	0.25	0.40
$X_{1,1}^{5*}$	0.1	0.25	0.25	0.4	0.6	0.75	0.75	0.9	0.06	0.19	0.19	0.36
$X_{1,2}^{5*}$	0.3	0.5	0.5	0.7	0.1	0.25	0.25	0.4	0.03	0.13	0.13	0.28
$X_{1,3}^{5*}$	0	0	0.1	0.2	0.3	0.5	0.5	0.7	0.00	0.00	0.05	0.14
$X_{3,1}^{5*}$	0	0	0.1	0.2	0.6	0.75	0.75	0.9	0.00	0.00	0.08	0.18
$X_{3,2}^{5*}$	0.1	0.25	0.25	0.4	0.3	0.5	0.5	0.7	0.03	0.13	0.13	0.28
$X_{2,1}^{5*}$	0.1	0.25	0.25	0.4	0.6	0.75	0.75	0.9	0.06	0.19	0.19	0.36
$X_{2,2}^{5*}$	0	0	0.1	0.2	0.3	0.5	0.5	0.7	0.00	0.00	0.05	0.14
$X_{2,3}^{5*}$	0.6	0.75	0.75	0.9	0.3	0.5	0.5	0.7	0.18	0.38	0.38	0.63
$X_{2,4}^{5*}$	0	0	0.1	0.2	0.3	0.5	0.5	0.7	0.00	0.00	0.05	0.14
$X_{2,1}^{4*}$	0	0	0.1	0.2	0.1	0.25	0.25	0.4	0.00	0.00	0.03	0.08
$X_{2,2}^{4*}$	0.3	0.5	0.5	0.7	0.3	0.5	0.5	0.7	0.09	0.25	0.25	0.49
$X_{2,3}^{4*}$	0	0	0.1	0.2	0.6	0.75	0.75	0.9	0.00	0.00	0.08	0.18
$X_{4,1}^{4*}$	0.1	0.25	0.25	0.4	0.6	0.75	0.75	0.9	0.06	0.19	0.19	0.36
$X_{4,2}^{4*}$	0.3	0.5	0.5	0.7	0.3	0.5	0.5	0.7	0.09	0.25	0.25	0.49
$X_{4,3}^{4*}$	0	0	0.1	0.2	0.3	0.5	0.5	0.7	0.00	0.00	0.05	0.14
$X_{4,4}^{4*}$	0.3	0.5	0.5	0.7	0.1	0.25	0.25	0.4	0.03	0.13	0.13	0.28
$X_{4,5}^{4*}$	0.3	0.5	0.5	0.7	0	0	0.1	0.2	0.00	0.00	0.05	0.14
$X_{3,1}^{4*}$	0.1	0.25	0.25	0.4	0.3	0.5	0.5	0.7	0.03	0.13	0.13	0.28

$X^{4*}_{3,2}$	0	0	0.1	0.2	0.1	0.25	0.25	0.4	0.00	0.00	0.03	0.08
$X^{4*}_{5,1}$	0.6	0.75	0.75	0.9	0.1	0.25	0.25	0.4	0.06	0.19	0.19	0.36
$X^{4*}_{5,2}$	0.3	0.5	0.5	0.7	0	0	0.1	0.2	0.00	0.00	0.05	0.14
$X^{4*}_{5,3}$	0.3	0.5	0.5	0.7	0	0	0.1	0.2	0.00	0.00	0.05	0.14
$X^{4*}_{5,4}$	0.3	0.5	0.5	0.7	0	0	0.1	0.2	0.00	0.00	0.05	0.14
$X^{3*}_{2,1}$	0.1	0.25	0.25	0.4	0.8	0.9	1	1	0.08	0.23	0.25	0.40
$X^{3*}_{2,2}$	0	0	0.1	0.2	0.6	0.75	0.75	0.9	0.00	0.00	0.08	0.18
$X^{3*}_{2,3}$	0.3	0.5	0.5	0.7	0.3	0.5	0.5	0.7	0.09	0.25	0.25	0.49

Table A2.5 Intersection results of all the evaluated risks over $TPFN_R$

X_{ij}	$TPFN_{LS}$				VL	L	M	H	VH
$X^{3*}_{3,2}$	0.00	0.00	0.10	0.20	1	1	0.45	0	0
$X^{4*}_{1,1}$	0.06	0.19	0.19	0.36	0	0.43	0.83	0	0
$X^{4*}_{1,2}$	0.08	0.23	0.25	0.40	0	0.31	1	0.1	0
$X^{5*}_{1,1}$	0.06	0.19	0.19	0.36	0	0.43	0.83	0	0
$X^{5*}_{1,2}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0
$X^{5*}_{1,3}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X^{5*}_{3,1}$	0.00	0.00	0.08	0.18	1	1	0.35	0	0
$X^{5*}_{3,2}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0
$X^{5*}_{2,1}$	0.06	0.19	0.19	0.36	0	0.43	0.83	0	0
$X^{5*}_{2,2}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X^{5*}_{2,3}$	0.18	0.38	0.38	0.63	0	0.73	0.6	0	0
$X^{5*}_{2,4}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X^{4*}_{2,1}$	0.00	0.00	0.03	0.08	1	0.7	0	0	0
$X^{4*}_{2,2}$	0.09	0.25	0.25	0.49	0	0.27	1	0.3	0

$X^{4*}_{2,3}$	0.00	0.00	0.08	0.18	1	1	0.35	0	0
$X^{4*}_{4,1}$	0.06	0.19	0.19	0.36	0	0.43	0.83	0	0
$X^{4*}_{4,2}$	0.09	0.25	0.25	0.49	0	0.27	1	0.3	0
$X^{4*}_{4,3}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X^{4*}_{4,4}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0
$X^{4*}_{4,5}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X^{4*}_{3,1}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0
$X^{4*}_{3,2}$	0.00	0.00	0.03	0.08	1	0.7	0	0	0
$X^{4*}_{5,1}$	0.06	0.19	0.19	0.36	0	0.43	0.83	0	0
$X^{4*}_{5,2}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X^{4*}_{5,3}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X^{4*}_{5,4}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X^{3*}_{2,1}$	0.08	0.23	0.25	0.40	0	0.31	1	0.1	0
$X^{3*}_{2,2}$	0.00	0.00	0.08	0.18	1	1	0.35	0	0
$X^{3*}_{2,3}$	0.09	0.25	0.25	0.49	0	0.27	1	0.3	0

Table A2.6 Normalised fuzzy risk

X_{ij}^*	VL	L	M	H	VH	VL	L	M	H	VH
$X^{3*}_{3,2}$	1	1	0.45	0	0	0.41	0.41	0.18	0.00	0.00
$X^{4*}_{1,1}$	0	0.43	0.83	0	0	0.00	0.34	0.66	0.00	0.00
$X^{4*}_{1,2}$	0	0.31	1	0.1	0	0.00	0.22	0.71	0.07	0.00
$X^{5*}_{1,1}$	0	0.43	0.83	0	0	0.00	0.34	0.66	0.00	0.00
$X^{5*}_{1,2}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X^{5*}_{1,3}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X^{5*}_{3,1}$	1	1	0.35	0	0	0.43	0.43	0.15	0.00	0.00
$X^{5*}_{3,2}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00

$X_{2,1}^{5*}$	0	0.43	0.83	0	0	0.00	0.34	0.66	0.00	0.00
$X_{2,2}^{5*}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X_{2,3}^{5*}$	0	0.73	0.6	0	0	0.00	0.55	0.45	0.00	0.00
$X_{2,4}^{5*}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X_{2,1}^{4*}$	1	0.7	0	0	0	0.59	0.41	0.00	0.00	0.00
$X_{2,2}^{4*}$	0	0.27	1	0.3	0	0.00	0.17	0.64	0.19	0.00
$X_{2,3}^{4*}$	1	1	0.35	0	0	0.43	0.43	0.15	0.00	0.00
$X_{4,1}^{4*}$	0	0.43	0.83	0	0	0.00	0.34	0.66	0.00	0.00
$X_{4,2}^{4*}$	0	0.27	1	0.3	0	0.00	0.17	0.64	0.19	0.00
$X_{4,3}^{4*}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X_{4,4}^{4*}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X_{4,5}^{4*}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X_{3,1}^{4*}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X_{3,2}^{4*}$	1	0.7	0	0	0	0.59	0.41	0.00	0.00	0.00
$X_{5,1}^{4*}$	0	0.43	0.83	0	0	0.00	0.34	0.66	0.00	0.00
$X_{5,2}^{4*}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X_{5,3}^{4*}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X_{5,4}^{4*}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X_{2,1}^{3*}$	0	0.31	1	0.1	0	0.00	0.22	0.71	0.07	0.00
$X_{2,2}^{3*}$	1	1	0.35	0	0	0.43	0.43	0.15	0.00	0.00
$X_{2,3}^{3*}$	0	0.27	1	0.3	0	0.00	0.17	0.64	0.19	0.00

Table A2.7 Result of the first stage of aggregative risk assessment

$X_{i,j}^5$	VL	L	M	H	VH	$w_{i,j}^5$	$X_{i,j}^5$	VL	L	M	H	VH	$w_{i,j}^4$
$X_{1,1}^{5*}$	0.00	0.34	0.66	0.00	0.00	0.250	$X_{1,1}^4$	0.153	0.427	0.420	0.000	0.000	0.330
$X_{1,2}^{5*}$	0.07	0.46	0.46	0.00	0.00	0.500							
$X_{1,3}^{5*}$	0.47	0.44	0.09	0.00	0.00	0.250							
$X_{3,1}^{5*}$	0.43	0.43	0.15	0.00	0.00	0.220	$X_{1,3}^4$	0.149	0.456	0.395	0.000	0.000	0.330
$X_{3,2}^{5*}$	0.07	0.46	0.46	0.00	0.00	0.780							
$X_{2,1}^{5*}$	0.00	0.34	0.66	0.00	0.00	0.290	$X_{1,2}^4$	0.126	0.459	0.415	0.000	0.000	0.330
$X_{2,2}^{5*}$	0.47	0.44	0.09	0.00	0.00	0.110							
$X_{2,3}^{5*}$	0.00	0.55	0.45	0.00	0.00	0.44							
$X_{2,4}^{5*}$	0.47	0.44	0.09	0.00	0.00	0.16							

Table A2.8 Result of the second stage of aggregative risk assessment

$X_{i,j}^4$	VL	L	M	H	VH	$w_{i,j}^4$	$X_{i,j}^3$	VL	L	M	H	VH
							$X_{3,2}^{3*}$	0.41	0.41	0.18	0.00	0.00
$X_{1,1}^{4*}$	0	0.43	0.83	0	0	0.500	$X_{3,1}^3$	0.000	0.370	0.915	0.050	0.000
$X_{1,2}^{4*}$	0	0.31	1	0.1	0	0.500						
$X_{1,1}^4$	0.153	0.427	0.420	0	0	0.330	$X_{1,1}^3$	0.141	0.443	0.406	0.000	0.000
$X_{1,3}^4$	0.149	0.456	0.395	0	0	0.330						
$X_{1,2}^4$	0.126	0.459	0.415	0	0	0.330						
$X_{2,1}^{4*}$	1	0.7	0	0	0	0.37	$X_{1,2}^3$	0.620	0.612	0.468	0.114	0.000
$X_{2,2}^{4*}$	0	0.27	1	0.3	0	0.38						
$X_{2,3}^{4*}$	1	1	0.35	0	0	0.25						
$X_{4,1}^{4*}$	0	0.43	0.83	0	0	0.22	$X_{1,4}^3$	0.362	0.617	0.614	0.066	0.000
$X_{4,2}^{4*}$	0	0.27	1	0.3	0	0.22						
$X_{4,3}^{4*}$	1	0.94	0.2	0	0	0.12						

$X^{4*}_{4,4}$	0.1	0.65	0.65	0	0	0.22						
$X^{4*}_{4,5}$	1	0.94	0.2	0	0	0.22						
$X^{4*}_{3,1}$	0.1	0.65	0.65	0	0	0.5	$X^{3}_{1,3}$	0.550	0.675	0.325	0.000	0.000
$X^{4*}_{3,2}$	1	0.7	0	0	0	0.5						
$X^{4*}_{5,1}$	0	0.43	0.83	0	0	0.25	$X^{3}_{1,5}$	0.750	0.813	0.358	0.000	0.000
$X^{4*}_{5,2}$	1	0.94	0.2	0	0	0.25						
$X^{4*}_{5,3}$	1	0.94	0.2	0	0	0.25						
$X^{4*}_{5,4}$	1	0.94	0.2	0	0	0.25						
							$X^{3*}_{2,1}$	0.00	0.22	0.71	0.07	0.00
							$X^{3*}_{2,2}$	0.43	0.43	0.15	0.00	0.00
							$X^{3*}_{2,3}$	0.00	0.17	0.64	0.19	0.00

Table A2.9 Result of the third stage of aggregative risk assessment

$X_{i,j}^{3}$	VL	L	M	H	VH	$w_{i,j}^{3}$	$X_{i,j}^{2}$	VL	L	M	H	VH
$X^{3*}_{3,2}$	0.41	0.41	0.18	0.00	0.00	0.200	$X^{2}_{1,3}$	0.082	0.378	0.768	0.040	0.000
$X^{3}_{3,1}$	0.000	0.370	0.915	0.050	0.000	0.800						
$X^{3}_{1,1}$	0.141	0.443	0.406	0.000	0.000	0.290	$X^{2}_{1,1}$	0.456	0.628	0.437	0.027	0.000
$X^{3}_{1,2}$	0.620	0.612	0.468	0.114	0.000	0.11						
$X^{3}_{1,4}$	0.362	0.617	0.614	0.066	0.000	0.22						
$X^{3}_{1,3}$	0.550	0.675	0.325	0.000	0.000	0.09						
$X^{3}_{1,5}$	0.750	0.813	0.358	0.000	0.000	0.29						
$X^{3*}_{2,1}$	0.00	0.22	0.71	0.07	0.00	0.25	$X^{2}_{1,2}$	0.065	0.213	0.552	0.122	0.000
$X^{3*}_{2,2}$	0.43	0.43	0.15	0.00	0.00	0.15						
$X^{3*}_{2,3}$	0.00	0.17	0.64	0.19	0.00	0.55						

Table A2.10 Result of the fourth stage and final AA of well leakage

$X_{i,j}^{2'}$	VL	L	M	H	VH	$w_{i,j}^{2}$		VL	L	M	H	VH
$X_{1,3}^{2}$	0.082	0.378	0.768	0.040	0.000	0.280	$X_{0,1}^{1}$	0.181	0.355	0.424	0.040	0
$X_{1,1}^{2}$	0.456	0.628	0.437	0.027	0.000	0.610	$L_G(P)$	0.014	0.077	0.276	0.577	0.858
$X_{1,2}^{2}$	0.065	0.213	0.552	0.122	0.000	0.11	X	0.170				

Table A2.11 BRIs of gas holders

$X_{i,j}^{*}$	$TPFN_L$				$TPFN_S$				$TPFN_{LS}$			
$X_{3,1}^{3*}$	0	0	0.1	0.2	0.8	0.9	1	1	0.00	0.00	0.10	0.20
$X_{3,2}^{3*}$	0.1	0.25	0.25	0.4	0.3	0.5	0.5	0.7	0.03	0.13	0.13	0.28
$X_{1,1}^{5*}$	0	0	0.1	0.2	0.6	0.75	0.75	0.9	0.00	0.00	0.08	0.18
$X_{1,2}^{5*}$	0	0	0.1	0.2	0.8	0.9	1	1	0.00	0.00	0.10	0.20
$X_{1,3}^{5*}$	0.3	0.5	0.5	0.7	0.3	0.5	0.5	0.7	0.09	0.25	0.25	0.49
$X_{1,4}^{5*}$	0	0	0.1	0.2	0.6	0.75	0.75	0.9	0.00	0.00	0.08	0.18
$X_{1,5}^{5*}$	0.1	0.25	0.25	0.4	0.8	0.9	1	1	0.08	0.23	0.25	0.40
$X_{1,6}^{5*}$	0.1	0.25	0.25	0.4	0.1	0.25	0.25	0.4	0.01	0.06	0.06	0.16
$X_{2,1}^{5*}$	0	0	0.1	0.2	0.3	0.5	0.5	0.7	0.00	0.00	0.05	0.14
$X_{2,2}^{5*}$	0	0	0.1	0.2	0.6	0.75	0.75	0.9	0.00	0.00	0.08	0.18
$X_{2,3}^{5*}$	0.1	0.25	0.25	0.4	0.6	0.75	0.75	0.9	0.06	0.19	0.19	0.36
$X_{2,4}^{5*}$	0	0	0.1	0.2	0.1	0.25	0.25	0.4	0.00	0.00	0.03	0.08
$X_{2,1}^{4*}$	0.1	0.25	0.25	0.4	0.3	0.5	0.5	0.7	0.03	0.13	0.13	0.28
$X_{2,2}^{4*}$	0	0	0.1	0.2	0.6	0.75	0.75	0.9	0.00	0.00	0.08	0.18
$X_{2,3}^{4*}$	0.3	0.5	0.5	0.7	0.3	0.5	0.5	0.7	0.09	0.25	0.25	0.49
$X_{1,1}^{5*}$	0.1	0.25	0.25	0.4	0.1	0.25	0.25	0.4	0.01	0.06	0.06	0.16
$X_{1,2}^{5*}$	0	0	0.1	0.2	0.3	0.5	0.5	0.7	0.00	0.00	0.05	0.14
$X_{2,1}^{5*}$	0	0	0.1	0.2	0.1	0.25	0.25	0.4	0.00	0.00	0.03	0.08
$X_{2,2}^{5*}$	0.1	0.25	0.25	0.4	0.1	0.25	0.25	0.4	0.01	0.06	0.06	0.16

$X_{2,1}^{3*}$	0	0	0.1	0.2	0.8	0.9	1	1	0.00	0.00	0.10	0.20
$X_{2,2}^{3*}$	0	0	0.1	0.2	0.8	0.9	1	1	0.00	0.00	0.10	0.20
$X_{2,3}^{3*}$	0.1	0.25	0.25	0.4	0.3	0.5	0.5	0.7	0.03	0.13	0.13	0.28

Table A2.12 Intersection results of all the evaluated risks over $TPFN_R$

X_{ij}^{*}	$TPFN_{LS}$				VL	L	M	H	VH
$X_{3,1}^{3*}$	0.00	0.00	0.10	0.20	1	1	0.45	0	0
$X_{3,2}^{3*}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0
$X_{1,1}^{5*}$	0.00	0.00	0.08	0.18	1	1	0.35	0	0
$X_{1,2}^{5*}$	0.00	0.00	0.10	0.20	1	1	0.45	0	0
$X_{1,3}^{5*}$	0.09	0.25	0.25	0.49	0	0.27	1	0.3	0
$X_{1,4}^{5*}$	0.00	0.00	0.08	0.18	1	1	0.35	0	0
$X_{1,5}^{5*}$	0.08	0.23	0.25	0.40	0	0.31	1	0.1	0
$X_{1,6}^{5*}$	0.01	0.06	0.06	0.16	0.35	1	0.26	0	0
$X_{2,1}^{5*}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X_{2,2}^{5*}$	0.00	0.00	0.08	0.18	1	1	0.35	0	0
$X_{2,3}^{5*}$	0.06	0.19	0.19	0.36	0	0.43	0.83	0	0
$X_{2,4}^{5*}$	0.00	0.00	0.03	0.08	1	0.7	0	0	0
$X_{2,1}^{4*}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0
$X_{2,2}^{4*}$	0.00	0.00	0.08	0.18	1	1	0.35	0	0
$X_{2,3}^{4*}$	0.09	0.25	0.25	0.49	0	0.27	1	0.3	0
$X_{1,1}^{5*}$	0.01	0.06	0.06	0.16	0.35	1	0.26	0	0
$X_{1,2}^{5*}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X_{2,1}^{5*}$	0.00	0.00	0.03	0.08	1	0.7	0	0	0
$X_{2,2}^{5*}$	0.01	0.06	0.06	0.16	0.35	1	0.26	0	0
$X_{2,1}^{3*}$	0.00	0.00	0.10	0.20	1	1	0.45	0	0

$X^{3*}_{2,2}$	0.00	0.00	0.10	0.20	1	1	0.45	0	0
$X^{3*}_{2,3}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0

Table A2.13 Normalised fuzzy risk

X^*_{ij}	VL	L	M	H	VH	VL	L	M	H	VH
$X^{3*}_{3,1}$	1	1	0.45	0	0	0.41	0.41	0.18	0.00	0.00
$X^{3*}_{3,2}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X^{5*}_{1,1}$	1	1	0.35	0	0	0.43	0.43	0.15	0.00	0.00
$X^{5*}_{1,2}$	1	1	0.45	0	0	0.41	0.41	0.18	0.00	0.00
$X^{5*}_{1,3}$	0	0.27	1	0.3	0	0.00	0.17	0.64	0.19	0.00
$X^{5*}_{1,4}$	1	1	0.35	0	0	0.43	0.43	0.15	0.00	0.00
$X^{5*}_{1,5}$	0	0.31	1	0.1	0	0.00	0.22	0.71	0.07	0.00
$X^{5*}_{1,6}$	0.35	1	0.26	0	0	0.22	0.62	0.16	0.00	0.00
$X^{5*}_{2,1}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X^{5*}_{2,2}$	1	1	0.35	0	0	0.43	0.43	0.15	0.00	0.00
$X^{5*}_{2,3}$	0	0.43	0.83	0	0	0.00	0.34	0.66	0.00	0.00
$X^{5*}_{2,4}$	1	0.7	0	0	0	0.59	0.41	0.00	0.00	0.00
$X^{4*}_{2,1}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X^{4*}_{2,2}$	1	1	0.35	0	0	0.43	0.43	0.15	0.00	0.00
$X^{4*}_{2,3}$	0	0.27	1	0.3	0	0.00	0.17	0.64	0.19	0.00
$X^{5*}_{1,1}$	0.35	1	0.26	0	0	0.22	0.62	0.16	0.00	0.00
$X^{5*}_{1,2}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X^{5*}_{2,1}$	1	0.7	0	0	0	0.59	0.41	0.00	0.00	0.00
$X^{5*}_{2,2}$	0.35	1	0.26	0	0	0.22	0.62	0.16	0.00	0.00
$X^{3*}_{2,1}$	1	1	0.45	0	0	0.41	0.41	0.18	0.00	0.00
$X^{3*}_{2,2}$	1	1	0.45	0	0	0.41	0.41	0.18	0.00	0.00

$X^{3*}_{2,3}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00

Table A2.14 Result of the first stage of aggregative risk assessment

$X_{i,j}^{*}$	VL	L	M	II	VII	$w_{i,j}^{5}$	$X_{i,j}^{4}$	VL	L	M	H	VH
$X^{5*}_{1,1}$	0.43	0.43	0.15	0.00	0.00	0.200	$X^{4}_{1,1}$	0.274	0.373	0.314	0.039	0.000
$X^{5*}_{1,2}$	0.41	0.41	0.18	0.00	0.00	0.200						
$X^{5*}_{1,3}$	0.00	0.17	0.64	0.19	0.00	0.150						
$X^{5*}_{1,4}$	0.43	0.43	0.15	0.00	0.00	0.200						
$X^{5*}_{1,5}$	0.00	0.22	0.71	0.07	0.00	0.150						
$X^{5*}_{1,6}$	0.22	0.62	0.16	0.00	0.00	0.100						
$X^{5*}_{2,1}$	0.47	0.44	0.09	0.00	0.00	0.200	$X^{4}_{1,2}$	0.347	0.400	0.254	0.000	0.000
$X^{5*}_{2,2}$	0.43	0.43	0.15	0.00	0.00	0.25						
$X^{5*}_{2,3}$	0.00	0.34	0.66	0.00	0.00	0.3						
$X^{5*}_{2,4}$	0.59	0.41	0.00	0.00	0.00	0.25						
$X^{5*}_{1,1}$	0.22	0.62	0.16	0.00	0.00	0.78	$X^{4}_{3,1}$	0.272	0.581	0.147	0.000	0.000
$X^{5*}_{1,2}$	0.47	0.44	0.09	0.00	0.00	0.22						
$X^{5*}_{2,1}$	0.59	0.41	0.00	0.00	0.00	0.64	$X^{4}_{3,2}$	0.455	0.487	0.058	0.000	0.000
$X^{5*}_{2,2}$	0.22	0.62	0.16	0.00	0.00	0.36						

Table A2.15 Result of the second stage of aggregative risk assessment

$X_{i,j}^{4}$	VL	L	M	II	VII	$w_{i,j}^{4}$	$X_{i,j}^{3}$	VL	L	M	H	VII
$X^{4}_{1,1}$	0.274	0.373	0.314	0.039	0.00	0.500	$X^{3}_{1,1}$	0.310	0.386	0.284	0.020	0.000
$X^{4}_{1,2}$	0.347	0.400	0.254	0.00	0.00	0.500						
$X^{4*}_{2,1}$	0.272	0.581	1	0.30	0.00	0.33	$X^{3}_{1,2}$	0.330	0.561	0.719	0.099	0.000
$X^{4*}_{2,2}$	0.00	0.00	0.35	0.00	0.00	0.33						
$X^{4*}_{2,3}$	0.455	0.487	0.83	0.00	0.00	0.33						

$X^4_{3,1}$	0.272	0.581	0.147	0.000	0.000	0.5	$X^3_{1,3}$	0.364	0.534	0.102	0.000	0.000
$X^4_{3,2}$	0.455	0.487	0.058	0.00	0.00	0.5						

Table A2.16 Result of the third stage of aggregative risk assessment

$X_{i,j}^3$	VL	L	M	H	VH	$w_{i,j}^3$	$X_{i,j}^2$	VL	L	M	H	VH
$X^{3*}_{3,1}$	0.41	0.41	0.18	0.00	0.00	0.220	$X^2_{1,3}$	0.145	0.449	0.398	0.000	0.000
$X^{3*}_{3,2}$	0.07	0.46	0.46	0.00	0.00	0.780						
$X^3_{1,1}$	0.310	0.386	0.284	0.020	0.000	0.300	$X^2_{1,1}$	0.341	0.495	0.280	0.026	0.000
$X^3_{1,2}$	0.330	0.561	0.719	0.099	0.000	0.2						
$X^3_{1,3}$	0.364	0.534	0.102	0.000	0.000	0.500						
$X^{3*}_{2,1}$	0.41	0.41	0.18	0.00	0.00	0.33	$X^2_{1,2}$	0.294	0.422	0.271	0.000	0.000
$X^{3*}_{2,2}$	0.41	0.41	0.18	0.00	0.00	0.33						
$X^{3*}_{2,3}$	0.07	0.46	0.46	0.00	0.00	0.33						

Table A2.17 Result of the fourth stage and final AA of gas holder leakage

$X_{i,j}^2$	VL	L	M	H	VH	$w_{i,j}^2$		VL	L	M	H	VH
$X^2_{1,3}$	0.145	0.449	0.398	0.000	0.000	0.220	$X^1_{0,1}$	0.270	0.449	0.268	0.013	0
$X^2_{1,1}$	0.341	0.495	0.280	0.026	0.000	0.680	$L_G(P)$	0.014	0.077	0.276	0.577	0.858
$X^2_{1,2}$	0.294	0.422	0.271	0.000	0.000	0.1	X	0.120				

Table A2.18 BRIs of gas pipelines

$X_{i,j}^{*}$	$TPFN_L$				$TPFN_S$				$TPFN_{LS}$			
$X^{3*}_{3,2}$	0	0	0.1	0.2	0.6	0.75	0.75	0.9	0.00	0.00	0.08	0.18
$X^{4*}_{1,1}$	0.3	0.5	0.5	0.7	0.8	0.9	1	1	0.24	0.45	0.50	0.70
$X^{4*}_{1,2}$	0.3	0.5	0.5	0.7	0.8	0.9	1	1	0.24	0.45	0.50	0.70
$X^{4*}_{1,1}$	0.3	0.5	0.5	0.7	0.3	0.5	0.5	0.7	0.09	0.25	0.25	0.49
$X^{4*}_{1,2}$	0.1	0.25	0.25	0.4	0.3	0.5	0.5	0.7	0.03	0.13	0.13	0.28
$X^{4*}_{2,1}$	0	0	0.1	0.2	0.3	0.5	0.5	0.7	0.00	0.00	0.05	0.14
$X^{4*}_{2,2}$	0	0	0.1	0.2	0.6	0.75	0.75	0.9	0.00	0.00	0.08	0.18

$X_{3,1}^{5*}$	0.1	0.25	0.25	0.4	0.3	0.5	0.5	0.7	0.03	0.13	0.13	0.28
$X_{3,2}^{5*}$	0.1	0.25	0.25	0.4	0.6	0.75	0.75	0.9	0.06	0.19	0.19	0.36
$X_{3,3}^{5*}$	0.3	0.5	0.5	0.7	0.3	0.5	0.5	0.7	0.09	0.25	0.25	0.49
$X_{4,1}^{4*}$	0.1	0.25	0.25	0.4	0.1	0.25	0.25	0.4	0.01	0.06	0.06	0.16
$X_{4,2}^{4*}$	0.3	0.5	0.5	0.7	0.6	0.75	0.75	0.9	0.18	0.38	0.38	0.63
$X_{2,1}^{3*}$	0	0	0.1	0.2	0.8	0.9	1	1	0.00	0.00	0.10	0.20
$X_{2,2}^{3*}$	0.1	0.25	0.25	0.4	0.8	0.9	1	1	0.08	0.23	0.25	0.40

Table A2.19 Intersection results of all the evaluated risks over $TPFN_R$

X_{ij}^{*}	$TPFN_{LS}$				VL	L	M	H	VH
$X_{3,2}^{3*}$	0.00	0.00	0.08	0.18	1	1	0.35	0	0
$X_{1,1}^{4*}$	0.24	0.45	0.50	0.70	0	0	0.58	0.85	0.15
$X_{1,2}^{4*}$	0.24	0.45	0.50	0.70	0	0	0.58	0.85	0.15
$X_{1,1}^{4*}$	0.09	0.25	0.25	0.49	0	0.27	1	0.3	0
$X_{1,2}^{4*}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0
$X_{2,1}^{4*}$	0.00	0.00	0.05	0.14	1	0.94	0.2	0	0
$X_{2,2}^{4*}$	0.00	0.00	0.08	0.18	1	1	0.35	0	0
$X_{3,1}^{5*}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0
$X_{3,2}^{5*}$	0.03	0.13	0.13	0.28	0.1	0.65	0.65	0	0
$X_{3,3}^{5*}$	0.09	0.25	0.25	0.49	0	0.27	1	0.3	0
$X_{4,1}^{4*}$	0.01	0.06	0.06	0.16	0.35	1	0.26	0	0
$X_{4,2}^{4*}$	0.18	0.38	0.38	0.63	0	0	0.73	0.6	0
$X_{2,1}^{3*}$	0.00	0.00	0.10	0.20	1	1	0.45	0	0
$X_{2,2}^{3*}$	0.08	0.23	0.25	0.40	0	0.31	1	0.1	0

Table A2.20 Normalised fuzzy risk

X_{ij}^{**}	VL	L	M	H	VH	VL	L	M	H	VH
$X_{3,2}^{3*}$	1	1	0.35	0	0	0.43	0.43	0.15	0.00	0.00
$X_{1,1}^{4*}$	0	0	0.58	0.85	0.15	0.00	0.00	0.37	0.54	0.09
$X_{1,2}^{4*}$	0	0	0.58	0.85	0.15	0.00	0.00	0.37	0.54	0.09
$X_{1,1}^{4*}$	0	0.27	1	0.3	0	0.00	0.17	0.64	0.19	0.00
$X_{1,2}^{4*}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X_{2,1}^{4*}$	1	0.94	0.2	0	0	0.47	0.44	0.09	0.00	0.00
$X_{2,2}^{4*}$	1	1	0.35	0	0	0.43	0.43	0.15	0.00	0.00
$X_{3,1}^{5*}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X_{3,2}^{5*}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X_{3,3}^{5*}$	0	0.27	1	0.3	0	0.00	0.17	0.64	0.19	0.00
$X_{4,1}^{4*}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X_{4,2}^{4*}$	0.1	0.65	0.65	0	0	0.07	0.46	0.46	0.00	0.00
$X_{2,1}^{3*}$	0	0.27	1	0.3	0	0.00	0.17	0.64	0.19	0.00
$X_{2,2}^{3*}$	0.35	1	0.26	0	0	0.22	0.62	0.16	0.00	0.00

Table A2.21 Result of the first stage of aggregative risk assessment

$X_{ij}^{5'}$	VL	L	M	H	VH	w_{ij}^{5}	$X_{ij}^{4'}$	VL	L	M	H	VH
$X_{3,1}^{5*}$	0.07	0.46	0.46	0.00	0.00	0.2	$X_{3,3}^{4}$	0.014	0.315	0.613	0.057	0.000
$X_{3,2}^{5*}$	0.00	0.34	0.66	0.00	0.00	0.5						
$X_{3,3}^{5*}$	0.00	0.17	0.64	0.19	0.00	0.3						

Table A2.22 Result of the second stage of aggregative risk assessment

$X_{i,j}^{4'}$	VL	L	M	H	VH	$w_{i,j}^{4}$	$X_{i,j}^{3'}$	VL	L	M	H	VH
$X_{1,1}^{4*}$	0	0.43	0.83	0	0	0.50	$X_{3,1}^{3}$	0.000	0.244	0.604	0.033	0
$X_{1,2}^{4*}$	0	0.31	1	0.1	0	0.50						
$X_{1,1}^{4*}$	0	0.17	0.64	0.19	0	0.68	$X_{1,1}^{3}$	0.022	0.263	0.582	0.129	0
$X_{1,2}^{4*}$	0.07	0.46	0.46	0	0	0.32						
$X_{2,1}^{4*}$	0.47	0.44	0.09	0	0	0.78	$X_{1,2}^{3}$	0.461	0.438	0.103	0.000	0
$X_{2,2}^{4*}$	0.43	0.43	0.15	0	0	0.22						
$X_{3,1}^{4*}$	0.071	0.464	0.464	0	0	0.40	$X_{1,3}^{3}$	0.054	0.424	0.511	0.011	0
$X_{3,1}^{4*}$	0.056	0.437	0.507	0	0	0.40						
$X_{3,3}^{4}$	0.014	0.315	0.613	0.057	0	0.2						
$X_{4,1}^{4*}$	0.22	0.62	0.16	0.0	0	0.5	$X_{1,4}^{3}$	0.110	0.310	0.355	0.225	0
$X_{4,2}^{4*}$	0	0	0.55	0.45	0	0.5						

Table A2.23 Result of the third stage of aggregative risk assessment

$X_{i,j}^{3'}$	VL	L	M	H	VH	$w_{i,j}^{3}$	$X_{i,j}^{2'}$	VL	L	M	H	VH
$X_{3,2}^{3*}$	0.41	0.41	0.18	0	0	0.220	$X_{1,3}^{2}$	0.090	0.281	0.511	0.026	0
$X_{3,1}^{3*}$	0	0.244	0.604	0.033	0	0.780						
$X_{1,1}^{3}$	0.022	0.263	0.582	0.129	0	0.20	$X_{1,1}^{2}$	0.123	0.365	0.425	0.087	0
$X_{1,2}^{3}$	0.461	0.438	0.103	0	0	0.150						
$X_{1,3}^{3}$	0.054	0.424	0.511	0.011	0	0.40						
$X_{1,4}^{3}$	0.110	0.310	0.355	0.225	0	0.25						
$X_{2,1}^{3*}$	0.41	0.41	0.18	0	0	0.3	$X_{1,2}^{2}$	0.123	0.277	0.551	0.049	0
$X_{2,2}^{3*}$	0	0.22	0.71	0.07	0	0.7						

Table A2.24 Result of the fourth stage and final AA of gas pipeline leakage

$X_{i,j}^{2'}$	VL	L	M	H	VH	$w_{i,j}^{2}$		VL	L	M	H	VH
$X_{1,3}^{2}$	0.090	0.281	0.511	0.026	0.000	0.210	$X_{0,1}^{1}$	0.116	0.299	0.416	0.153	0.016
$X_{1,1}^{2}$	0.123	0.365	0.425	0.064	0.023	0.700	$L_G(P)$	0.014	0.077	0.276	0.577	0.858
$X_{1,2}^{2}$	0.123	0.277	0.551	0.049	0.000	0.09	X	0.241				

Table A2.25 Result of AA of an OGSS

Risks of subsystems	VL	L	M	H	VH	*Weights of subsystems*	FAR of the OGSS	VL	L	M	H	VH
Risk of gas holder	0.270	0.449	0.268	0.013	0	0.16	$X_{0,1}^{1}$	0.164	0.351	0.403	0.076	0.006
Risk of gas pipeline	0.116	0.299	0.416	0.153	0.016	0.38	$L_G(P)$	0.014	0.077	0.276	0.577	0.858
Risk of gas well	0.181	0.355	0.424	0.040	0	0.38	X	0.190				
Risk of gas compressor	0.100	0.381	0.513	0.006	0	0.08						

Appendix 3

Table A3.1 Gas well hazard probabilities

Well pipeline hazard	Fault tree Ref.	Hazard failure rate	Well pipeline hazard	Fault tree Ref.	Hazard failure rate
1.Cementing job	H_{1111}	Linguistic term	16.PMV fail to isolate	H_{142}	Failure rate
2.Age	H_{1112}	Linguistic term	17.TCP failure	H_{143}	Failure rate
3.Water infiltration	H_{1113}	Linguistic term	18.PWV leakage	H_{144}	Failure rate
4.High temperature	H_{1121}	Linguistic term	19.PT leakage	H_{145}	Failure rate
5.Type of well completion	H_{1122}	Linguistic term	20.Flange failure	H_{151}	Failure rate
6.Galvanic corrosion	H_{1123}	Failure rate	21.AVV failure	H_{152}	Failure rate
7.Tension stress	H_{1124}	Failure rate	22.AMV failure	H_{153}	Failure rate
8.Carbonation of cement	H_{1131}	Linguistic term	23.AWV failure	H_{154}	Failure rate
9.Age of cement	H_{1132}	Linguistic term	24.Ground movement	H_{21}	Failure rate
10.Marine fouling	H_{121}	Failure rate	25.Ice collision	H_{22}	Linguistic term
11.Bio corrosion	H_{122}	Failure rate	26.High temperature	H_{23}	Failure rate
12.Cement carbonation	H_{123}	Linguistic term	27.Collision with ship	H_{311}	Linguistic term
13.Abrasion of well	H_{131}	Failure rate	28.Fishing trawler	H_{312}	Linguistic term
14.Hydrate formation	H_{132}	Linguistic term	29.Terrorist activity	H_{32}	Linguistic term
15.SSSV fail to isolate	H_{141}	Failure rate			

Table A3.2 Expert judgments on BEs with unknown failure rate

BEs	Well BEs judgements		
	E_1	E_2	E_3
H_{1111}	L	M	L
H_{1112}	M	M	H
H_{1113}	M	M	M
H_{1121}	M	H	H
H_{1122}	L	M	L
H_{1131}	M	M	M
H_{1132}	L	M	M
H_{123}	M	M	M
H_{132}	L	VL	L
H_{22}	VL	VL	VL
H_{311}	VL	M	L
H_{312}	L	L	L
H_{32}	VL	VL	L

Table A3.3 Aggregation calculation for the BE of H_{1111}

	H1111			
E1	0.1	0.25	0.25	0.4
E2	0.3	0.5	0.5	0.7
E3	0.1	0.25	0.25	0.4
SD12	1.25			
SD13	1			
SD23	1.25			
AD(E1)	1.125			
AD(E2)	1.25			
AD(E3)	1.125			
RDA(E1)	0.321			
RDA(E2)	0.357			
RDA(E3)	0.321			
CD(E1)	0.335			
CD(E2)	0.328			
CD(E3)	0.335			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.165	0.332	0.332	0.498
DF	0.332			
FP	0.002			

Table A3.4 Aggregation calculation for the BE of H_{1112}

	H1112			
E1	0.3	0.5	0.5	0.7
E2	0.3	0.5	0.5	0.7
E3	0.6	0.75	0.75	0.9
SD12	1			
SD13	1.25			
SD23	0.75			
AD(E1)	1.125			
AD(E2)	0.875			
AD(E3)	1			
RDA(E1)	0.375			
RDA(E2)	0.291			
RDA(E3)	0.333			
CD(E1)	0.362			
CD(E2)	0.295			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.402	0.585	0.585	0.768
DF	0.585			
FP	0.015			

Table A3.5 Aggregation calculation for the BE of H_{1113}

	H1113			
E1	0.3	0.5	0.5	0.7
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.3	0.5	0.5	0.7
DF	0.5			
FP	0.009			

Table A3.6 Aggregation calculation for the BE of H_{1121}

	H1121			
E1	0.1	0.25	0.25	0.4
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	1.25			
SD13	1.25			
SD23	1			
AD(E1)	1.25			
AD(E2)	1.125			
AD(E3)	1.125			
RDA(E1)	0.357			
RDA(E2)	0.321			
RDA(E3)	0.321			
CD(E1)	0.353			
CD(E2)	0.310			
CD(E3)	0.335			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.229	0.411	0.411	0.593
DF	0.411			
FP	0.005			

Table A3.7 Aggregation calculation for the BE of H_{1122}

	H1122			
E1	0.1	0.25	0.25	0.4
E2	0.3	0.5	0.5	0.7
E3	0.1	0.25	0.25	0.4
SD12	1.25			
SD13	1			
SD23	1.25			
AD(E1)	1.125			
AD(E2)	1.25			
AD(E3)	1.125			
RDA(E1)	0.321			
RDA(E2)	0.357			
RDA(E3)	0.321			
CD(E1)	0.335			
CD(E2)	0.328			
CD(E3)	0.335			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.165	0.332	0.332	0.498
DF	0.332			
FP	0.002			

Table A3.8 Aggregation calculation for the BE of H_{1131}

	H1131			
E1	0.3	0.5	0.5	0.7
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.3	0.5	0.5	0.7
DF	0.5			
FP	0.009			

Table A3.9 Aggregation calculation for the BE of H_{1132}

	H1132			
E1	0.1	0.25	0.25	0.4
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	1.25			
SD13	1.25			
SD23	1			
AD(E1)	1.25			
AD(E2)	1.125			
AD(E3)	1.125			
RDA(E1)	0.357			
RDA(E2)	0.321			
RDA(E3)	0.321			
CD(E1)	0.353			
CD(E2)	0.310			
CD(E3)	0.335			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.229	0.411	0.411	0.593
DF	0.411			
FP	0.005			

Table A3.10 Aggregation calculation for the BE of H_{123}

	H1131			
E1	0.3	0.5	0.5	0.7
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.3	0.5	0.5	0.7
DF	0.5			
FP	0.009			

Table A3.11 Aggregation calculation for the BE of H_{132}

	H132			
E1	0.1	0.25	0.25	0.4
E2	0	0	0.1	0.2
E3	0.1	0.25	0.25	0.4
SD12	0.825			
SD13	1			
SD23	0.825			
AD(E1)	0.912			
AD(E2)	0.825			
AD(E3)	0.912			
RDA(E1)	0.344			
RDA(E2)	0.311			
RDA(E3)	0.344			
CD(E1)	0.347			
CD(E2)	0.305			
CD(E3)	0.347			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.069	0.173	0.204	0.338868
DF	0.19			
FP	0.0005			

Table A3.12 Aggregation calculation for the BE of H_{22}

	H22			
E1	0	0	0.1	0.2
E2	0	0	0.1	0.2
E3	0	0	0.1	0.2
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.341			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0	0	0.1	0.2
DF	0.077			
FP	2.3E-05			

Table A3.13 Aggregation calculation for the BE of H_{311}

	H311			
E1	0	0	0.1	0.2
E2	0.3	0.5	0.5	0.7
E3	0.1	0.25	0.25	0.4
SD12	1.425			
SD13	1.175			
SD23	1.25			
AD(E1)	1.3			
AD(E2)	1.337			
AD(E3)	1.212			
RDA(E1)	0.337			
RDA(E2)	0.347			
RDA(E3)	0.314			
CD(E1)	0.343			
CD(E2)	0.323			
CD(E3)	0.332			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.130	0.244	0.279	0.428
DF	0.273			
FP	0.0015			

Table A3.14 Aggregation calculation for the BE of H_{312}

	H312			
E1	0.1	0.25	0.25	0.4
E2	0.1	0.25	0.25	0.4
E3	0.1	0.25	0.25	0.4
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.1	0.25	0.25	0.4
DF	0.25			
FP	0.0011			

Table A3.15 Aggregation calculation for the BE of H_{32}

	H32			
E1	0	0	0.1	0.2
E2	0	0	0.1	0.2
E3	0.1	0.25	0.25	0.4
SD12	1			
SD13	1.175			
SD23	0.825			
AD(E1)	1.0875			
AD(E2)	0.9125			
AD(E3)	1			
RDA(E1)	0.362			
RDA(E2)	0.304			
RDA(E3)	0.333			
CD(E1)	0.356			
CD(E2)	0.302			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.034	0.085	0.151	0.268
DF	0.137			
FP	0.00018			

Table A3.16 Importance level and TE probability of each MC

MC probability	TE probability=0.136	Importance measure	Ranking of MCs
0.0027		0.0197	17
0.0154		0.1129	1
0.0093		0.0681	6
0.0051		0.0373	14
0.0027		0.0197	17
0.0065		0.0476	11
0.0012		0.0087	20
0.000045		0.0003	27
0.0009		0.0065	22
0.0135		0.0989	2
0.0093		0.0681	6
0.0075		0.0549	10
0.0005		0.0036	24
0.0085		0.0623	8
0.0045		0.0329	16
0.0078		0.0571	9
0.0065		0.0476	11
0.0099		0.0725	3
0.0004		0.0029	25

0.0094		0.0689	5
0.0095		0.0696	4
0.0062		0.0454	13
0.0008		0.0058	23
0.00002		0.0001	28
0.0051		0.0373	14
0.0015		0.0109	19
0.0011		0.008	21
0.0001		0.0007	26

Table A3.17 Gas holder hazard probabilities

Gas holder hazard	Fault tree Ref.	Hazard failure rate	Gas holder hazard	Fault tree Ref.	Hazard failure rate
1.PRR failure	H_{1111}	Linguistic term	12.Inadequate strength	H_{122}	Linguistic term
2.Automatic interruption not successful	H_{1112}	Linguistic term	13.Heavy load	H_{123}	Linguistic term
3.Manual filling interruption not successful	H_{1113}	Linguistic term	14.Coating	H_{1311}	Linguistic term
4.PV failure	H_{1114}	Failure rate	15.Atmosphric conditions	H_{1312}	Linguistic term
5.PIA failure	H_{1115}	Linguistic term	16.Gas components	H_{1321}	Linguistic term
6.PS failure	H_{11116}	Linguistic term	17.Internal coating	H_{1322}	Linguistic term
7.SRVs failure	H_{1121}	Failure rate	18.Ground movement	H_{21}	Failure rate
8.RD failure	H_{1122}	Linguistic term	19.Lighting	H_{22}	Linguistic term
9.Fire protection failure	H_{1123}	Linguistic term	20.Flood	H_{23}	Linguistic term
10. TPV failure	H_{1124}	Linguistic term	21.Terrorist activity	H_{31}	Linguistic term
11.Unsuitable material	H_{121}	Linguistic term	22.Inadequate maintenance	H_{32}	Linguistic term

Table A3.18 Expert judgments on BEs with unknown failure rate

BEs	Well BEs judgements		
	E_1	E_2	E_3
H_{1111}	M	M	VL
H_{1112}	L	VL	L
H_{1113}	M	L	L
H_{1115}	L	L	L
H_{1116}	VL	M	VL
H_{1122}	VL	VL	VL
H_{1123}	L	L	M
H_{1124}	M	L	M
H_{121}	M	M	M
H_{122}	L	L	VL
H_{123}	H	L	M
H_{1311}	M	M	M
H_{1312}	H	M	M
H_{1321}	H	H	M
H_{1322}	L	M	L
H_{22}	VL	VL	VL
H_{23}	VL	M	VL
H_{31}	L	M	VL
H_{32}	VL	L	VL

Table A3.19 Aggregation calculation for the BE of H_{1111}

	H1111			
E1	0.3	0.5	0.5	0.7
E2	0.3	0.5	0.5	0.7
E3	0	0	0.1	0.2
SD12	1			
SD13	0.575			
SD23	1.425			
AD(E1)	0.787			
AD(E2)	1.212			
AD(E3)	1			
RDA(E1)	0.262			
RDA(E2)	0.404			
RDA(E3)	0.333			
CD(E1)	0.306			
CD(E2)	0.352			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.197	0.329	0.363	0.529
DF	0.357			
FP	0.003			

Table A3.20 Aggregation calculation for the BE of H_{1112}

	H1112			
E1	0.1	0.25	0.25	0.4
E2	0	0	0.1	0.2
E3	0	0	0.1	0.2
SD12	0.825			
SD13	0.825			
SD23	1			
AD(E1)	0.825			
AD(E2)	0.912			
AD(E3)	0.912			
RDA(E1)	0.311			
RDA(E2)	0.344			
RDA(E3)	0.344			
CD(E1)	0.33			
CD(E2)	0.322			
CD(E3)	0.347			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.0330	0.082	0.149	0.266
DF	0.135			
FP	0.0001			

Table A3.21 Aggregation calculation for the BE of H_{1113}

	H1113			
E1	0.3	0.5	0.5	0.7
E2	0.1	0.25	0.25	0.4
E3	0.1	0.25	0.25	0.4
SD12	0.75			
SD13	0.75			
SD23	1			
AD(E1)	0.75			
AD(E2)	0.875			
AD(E3)	0.875			
RDA(E1)	0.3			
RDA(E2)	0.35			
RDA(E3)	0.35			
CD(E1)	0.325			
CD(E2)	0.325			
CD(E3)	0.35			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.165	0.33125	0.33125	0.4975
DF	0.331			
FP	0.002			

Table A3.22 Aggregation calculation for the BE of H_{1115}

	H1115			
E1	0.1	0.25	0.25	0.4
E2	0.1	0.25	0.25	0.4
E3	0.1	0.25	0.25	0.4
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.1	0.25	0.25	0.4
DF	0.25			
FP	0.001			

Table A3.23 Aggregation calculation for the BE of H_{1116}

	H1116			
E1	0	0	0.1	0.2
E2	0.3	0.5	0.5	0.7
E3	0	0	0.1	0.2
SD12	1.425			
SD13	1			
SD23	1.425			
AD(E1)	1.212			
AD(E2)	1.425			
AD(E3)	1.212			
RDA(E1)	0.314			
RDA(E2)	0.370			
RDA(E3)	0.314			
CD(E1)	0.332			
CD(E2)	0.335			
CD(E3)	0.332			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.100	0.167	0.234	0.367
DF	0.22			
FP	0.0008			

Table A3.24 Aggregation calculation for the BE of H_{1122}

	H1122			
E1	0.1	0.25	0.25	0.4
E2	0.1	0.25	0.25	0.4
E3	0.1	0.25	0.25	0.4
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.1	0.25	0.25	0.4
DF	0.25			
FP	0.001			

Table A3.25 Aggregation calculation for the BE of H_{1123}

	H1123			
E1	0.1	0.25	0.25	0.4
E2	0.1	0.25	0.25	0.4
E3	0.3	0.5	0.5	0.7
SD12	1			
SD13	1.25			
SD23	0.75			
AD(E1)	1.125			
AD(E2)	0.875			
AD(E3)	1			
RDA(E1)	0.375			
RDA(E2)	0.291			
RDA(E3)	0.333			
CD(E1)	0.362			
CD(E2)	0.295			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.168	0.335	0.335	0.502
DF	0.335			
FP	0.002			

Table A3.26 Aggregation calculation for the BE of H_{1124}

	H1124			
E1	0.3	0.5	0.5	0.7
E2	0.1	0.25	0.25	0.4
E3	0.3	0.5	0.5	0.7
SD12	0.75			
SD13	1			
SD23	0.75			
AD(E1)	0.875			
AD(E2)	0.75			
AD(E3)	0.875			
RDA(E1)	0.35			
RDA(E2)	0.3			
RDA(E3)	0.35			
CD(E1)	0.35			
CD(E2)	0.3			
CD(E3)	0.35			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.24	0.425	0.425	0.61
DF	0.425			
FP	0.005			

Table A3.27 Aggregation calculation for the BE of H_{121}

	H121			
E1	0.3	0.5	0.5	0.7
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.3	0.5	0.5	0.7
DF	0.5			
FP	0.009			

Table A3.28 Aggregation calculation for the BE of H_{122}

	H122			
E1	0.1	0.25	0.25	0.4
E2	0.1	0.25	0.25	0.4
E3	0	0	0.1	0.2
SD12	1			
SD13	0.825			
SD23	1.175			
AD(E1)	0.912			
AD(E2)	1.087			
AD(E3)	1			
RDA(E1)	0.304			
RDA(E2)	0.362			
RDA(E3)	0.333			
CD(E1)	0.327			
CD(E2)	0.331			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.065833	0.164583	0.19875	0.331667
DF	0.192			
FP	0.0005			

Table A3.29 Aggregation calculation for the BE of H_{123}

	H123			
E1	0.6	0.75	0.75	0.9
E2	0.1	0.25	0.25	0.4
E3	0.3	0.5	0.5	0.7
SD12	0.5			
SD13	0.75			
SD23	0.75			
AD(E1)	0.625			
AD(E2)	0.625			
AD(E3)	0.75			
RDA(E1)	0.312			
RDA(E2)	0.312			
RDA(E3)	0.375			
CD(E1)	0.331			
CD(E2)	0.306			
CD(E3)	0.3625			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.338	0.506	0.506	0.674
DF	0.506			
FP	0.0096			

Table A3.30 Aggregation calculation for the BE of H_{1311}

	H121			
E1	0.3	0.5	0.5	0.7
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.3	0.5	0.5	0.7
DF	0.5			
FP	0.009			

Table A3.31 Aggregation calculation for the BE of H_{1312}

	H1312			
E1	0.6	0.75	0.75	0.9
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	0.75			
SD13	0.75			
SD23	1			
AD(E1)	0.75			
AD(E2)	0.875			
AD(E3)	0.875			
RDA(E1)	0.3			
RDA(E2)	0.35			
RDA(E3)	0.35			
CD(E1)	0.325			
CD(E2)	0.325			
CD(E3)	0.35			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.395	0.581	0.581	0.765
DF	0.581			
FP	0.015			

Table A3.32 Aggregation calculation for the BE of H_{1321}

	H1321			
E1	0.6	0.75	0.75	0.9
E2	0.6	0.75	0.75	0.9
E3	0.3	0.5	0.5	0.7
SD12	1			
SD13	0.75			
SD23	1.25			
AD(E1)	0.875			
AD(E2)	1.125			
AD(E3)	1			
RDA(E1)	0.291			
RDA(E2)	0.375			
RDA(E3)	0.333			
CD(E1)	0.320			
CD(E2)	0.337			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.497	0.664	0.664	0.831
DF	0.664			
FP	0.024			

Table A3.33 Aggregation calculation for the BE of H_{1322}

	H1322			
E1	0.1	0.25	0.25	0.4
E2	0.3	0.5	0.5	0.7
E3	0.1	0.25	0.25	0.4
SD12	1.25			
SD13	1			
SD23	1.25			
AD(E1)	1.125			
AD(E2)	1.25			
AD(E3)	1.125			
RDA(E1)	0.321			
RDA(E2)	0.357			
RDA(E3)	0.321			
CD(E1)	0.335			
CD(E2)	0.328			
CD(E3)	0.335			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.165	0.332	0.332	0.498
DF	0.332			
FP	0.0027			

Table A3.34 Aggregation calculation for the BE of H_{22}

	H22			
E1	0	0	0.1	0.2
E2	0	0	0.1	0.2
E3	0	0	0.1	0.2
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0	0	0.1	0.2
DF	0.077			
FP	2.3E-05			

Table A3.35 Aggregation calculation for the BE of H_{23}

	H23			
E1	0	0	0.1	0.2
E2	0.3	0.5	0.5	0.7
E3	0	0	0.1	0.2
SD12	1.425			
SD13	1			
SD23	1.42			
AD(E1)	1.21			
AD(E2)	1.42			
AD(E3)	1.21			
RDA(E1)	0.314			
RDA(E2)	0.370			
RDA(E3)	0.314			
CD(E1)	0.332			
CD(E2)	0.335			
CD(E3)	0.332			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.100	0.167	0.234	0.367
DF	0.22			
FP	0.0008			

Table A3.36 Aggregation calculation for the BE of H_{31}

	H31			
E1 E2 E3	0.1 0.3 0	0.25 0.5 0	0.25 0.5 0.1	0.4 0.75 0.2
SD12 SD13 SD23	1.26 0.825 1.43			
AD(E1) AD(E2) AD(E3)	1.04 1.35 1.13			
RDA(E1) RDA(E2) RDA(E3)	0.296 0.382 0.320			
CD(E1) CD(E2) CD(E3)	0.323 0.341 0.335			
W1 W2 W3	0.35 0.3 0.35			
AG	0.134752	0.251507	0.285053	0.452429
DF	0.284			
FP	0.0017			

Table A3.37 Aggregation calculation for the BE of H_{32}

	H32			
E1 E2 E3	0 0.1 0	0 0.25 0	0.1 0.25 0.1	0.2 0.4 0.2
SD12 SD13 SD23	1.175 1 1.175			
AD(E1) AD(E2) AD(E3)	1.087 1.175 1.087			
RDA(E1) RDA(E2) RDA(E3)	0.324 0.350 0.324			
CD(E1) CD(E2) CD(E3)	0.337 0.325 0.337			
W1 W2 W3	0.35 0.3 0.35			
AG	0.032	0.081	0.148	0.265
DF	0.135			
FP	0.00017			

Table A3.38 Importance level and TE probability of each MC

MC probability	TE probability=0.0425	Importance measure	Ranking of MCs
0.0033		0.0774	5
0.0001		0.0023	15
0.0027		0.0633	7
0.0002		0.0046	13
0.0011		0.0258	9
0.0008		0.0187	10
0.0045		0.1053	4
0.00002		0.0004	19
0.0028		0.0657	6
0.0056		0.1314	3
0.0093		0.2183	2
0.0005		0.0117	12
0.0096		0.2253	1
0.0001		0.0023	15
0.00006		0.0014	17
0.00003		0.0007	18
0.00002		0.0004	19
0.0008		0.0187	10
0.0017		0.0399	8

Table A3.39 Gas compressor hazard probabilities

Compressor hazard	Fault tree Ref.	Hazard failure rate	Compressor hazard	Fault tree Ref.	Hazard failure rate
1.Rotor failure	H_{1111}	Linguistic term	11.Impeller seal failure	H_{122}	Linguistic term
2.Brush failure	H_{1112}	Failure rate	12.Alarm failure	H_{13}	Failure rate
3.Engine failure	H_{1113}	Failure rate	13.Inadequate backup	H_{14}	Linguistic term
4.Liner supply failure	H_{1121}	Linguistic term	14.Gas meter corrosion	H_{15}	Failure rate
5.Switch failure	H_{1122}	Linguistic term	15.Small bore fitting failure	H_{16}	Failure rate
6.Fuse unit failure	H_{1123}	Linguistic term	16.Current turbidity	H_{21}	Failure rate
7.Impeller failure	H_{121}	Failure rate	17.Ground movement	H_{22}	Linguistic term
8.Impeller shaft failure	H_{122}	Failure rate	18.Terrorist activity	H_{31}	Linguistic term
9.Shaft bearing failure	H_{123}	Failure rate	19.Incorrect operation	H_{32}	Linguistic term
10. Shaft seal failure	H_{121}	Linguistic term			

Table A3.40 Expert judgments on BEs with unknown failure rate

BEs	Well BEs judgements		
	E_1	E_2	E_3
H_{1111}	L	M	M
H_{1121}	L	L	L
H_{1122}	L	M	L
H_{1123}	VL	L	L
H_{121}	M	M	M
H_{122}	M	L	M
H_{14}	VL	VL	M
H_{22}	M	L	M
H_{31}	L	L	L
H_{31}	VL	L	L

Table A3.41 Aggregation calculation for the BE of H_{121}

	H121			
E1	0.3	0.5	0.5	0.7
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.341			
CD(E2)	0.316			
CD(E3)	0.341			
W1	0.35			
W2	0.3			
W3	0.35			
AG	0.3	0.5	0.5	0.7
DF	0.5			
FP	0.009			

Table A3.42 Aggregation calculation for the BE of H_{122}

	H122			
E1	0.3	0.5	0.5	0.7
E2	0.1	0.25	0.25	0.4
E3	0.3	0.5	0.5	0.7
SD12	0.75			
SD13	1			
SD23	0.75			
AD(E1)	0.875			
AD(E2)	0.75			
AD(E3)	0.875			
RDA(E1)	0.35			
RDA(E2)	0.3			
RDA(E3)	0.35			
CD(E1)	0.355			
CD(E2)	0.315			
CD(E3)	0.33			
W1	0.36			
W2	0.33			
W3	0.31			
AG	0.237	0.421	0.421	0.605
DF	0.4212			
FP	0.0055			

Table A3.43 Aggregation calculation for the BE of H_{14}

	H14			
E1	0	0	0.1	0.2
E2	0.1	0.25	0.25	0.4
E3	0	0	0.1	0.2
SD12	1.175			
SD13	1			
SD23	1.175			
AD(E1)	1.087			
AD(E2)	1.175			
AD(E3)	1.087			
RDA(E1)	0.324			
RDA(E2)	0.350			
RDA(E3)	0.324			
CD(E1)	0.342			
CD(E2)	0.340			
CD(E3)	0.317			
W1	0.36			
W2	0.33			
W3	0.31			
AG	0.034	0.085	0.151	0.268
DF	0.137			
FP	0.0001			

Table A3.44 Aggregation calculation for the BE of H_{22}

	H22			
E1	0.3	0.5	0.5	0.7
E2	0.1	0.25	0.25	0.4
E3	0.3	0.5	0.5	0.7
SD12	0.75			
SD13	1			
SD23	0.75			
AD(E1)	0.875			
AD(E2)	0.75			
AD(E3)	0.875			
RDA(E1)	0.35			
RDA(E2)	0.3			
RDA(E3)	0.35			
CD(E1)	0.355			
CD(E2)	0.315			
CD(E3)	0.33			
W1	0.36			
W2	0.33			
W3	0.31			
AG	0.237	0.421	0.421	0.605
DF	0.421			
FP	0.0055			

Table A3.45 Aggregation calculation for the BE of H_{31}

	H31			
E1	0.1	0.25	0.25	0.4
E2	0.1	0.25	0.25	0.4
E3	0.1	0.25	0.25	0.4
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.346			
CD(E2)	0.331			
CD(E3)	0.321			
W1	0.36			
W2	0.33			
W3	0.31			
AG	0.1	0.25	0.25	0.4
DF	0.25			
FP	0.0011			

Table A3.46 Aggregation calculation for the BE of H_{32}

	H32			
E1	0	0	0.1	0.2
E2	0.1	0.25	0.25	0.4
E3	0.1	0.25	0.25	0.4
SD12	1.175			
SD13	1.175			
SD23	1			
AD(E1)	1.175			
AD(E2)	1.087			
AD(E3)	1.087			
RDA(E1)	0.350			
RDA(E2)	0.324			
RDA(E3)	0.324			
CD(E1)	0.355			
CD(E2)	0.327			
CD(E3)	0.317			
W1	0.36			
W2	0.33			
W3	0.31			
AG	0.06	0.16	0.19	0.32
DF	0.19			
FP	0.0005			

Table A3.47 Importance level and TE probability of each MC of compressor leakage

MC probability	TE probability=0.0401	Importance measure	Ranking of MCs
0.0093		0.229732891	2
0.0055		0.135863538	4
0.0085		0.209970922	3
0.0001		0.002470246	8
0.016		0.395239382	1
0.0002		0.004940492	7
0.000004		9.88098E-05	10
0.000045		0.001111611	9
0.00055		0.013586354	6

Table A3.48 Aggregation calculation for the BE of H_{1111}

	H1111			
E1	0.1	0.25	0.25	0.4
E2	0.3	0.5	0.5	0.7
E3	0.3	0.5	0.5	0.7
SD12	1.25			
SD13	1.25			
SD23	1			
AD(E1)	1.25			
AD(E2)	1.125			
AD(E3)	1.125			
RDA(E1)	0.357			
RDA(E2)	0.321			
RDA(E3)	0.321			
CD(E1)	0.358			
CD(E2)	0.325			
CD(E3)	0.315			
W1	0.36			
W2	0.33			
W3	0.31			
AG	0.228	0.410	0.410	0.592
DF	0.41			
FP	0.0051			

Table A3.49 Aggregation calculation for the BE of H_{1121}

	H1121			
E1	0.1	0.25	0.25	0.4
E2	0.1	0.25	0.25	0.4
E3	0.1	0.25	0.25	0.4
SD12	1			
SD13	1			
SD23	1			
AD(E1)	1			
AD(E2)	1			
AD(E3)	1			
RDA(E1)	0.333			
RDA(E2)	0.333			
RDA(E3)	0.333			
CD(E1)	0.346			
CD(E2)	0.331			
CD(E3)	0.321			
W1	0.36			
W2	0.33			
W3	0.31			
AG	0.1	0.25	0.25	0.4
DF	0.25			
FP	0.0011			

Table A3.50 Aggregation calculation for the BE of H_{1122}

	H1122			
E1	0.1	0.25	0.25	0.4
E2	0.3	0.5	0.5	0.7
E3	0.1	0.25	0.25	0.4
SD12	1.25			
SD13	1			
SD23	1.25			
AD(E1)	1.125			
AD(E2)	1.25			
AD(E3)	1.125			
RDA(E1)	0.321			
RDA(E2)	0.357			
RDA(E3)	0.321			
CD(E1)	0.340			
CD(E2)	0.343			
CD(E3)	0.315			
W1	0.36			
W2	0.33			
W3	0.31			
AG	0.168	0.335	0.335	0.503
DF	0.335			
FP	0.0028			

Table A3.51 Aggregation calculation for the BE of H_{1123}

	H1123			
E1	0	0	0.1	0.2
E2	0.1	0.25	0.25	0.4
E3	0.1	0.25	0.25	0.4
SD12	1.175			
SD13	1.175			
SD23	1			
AD(E1)	1.175			
AD(E2)	1.087			
AD(E3)	1.087			
RDA(E1)	0.350			
RDA(E2)	0.324			
RDA(E3)	0.324			
CD(E1)	0.355			
CD(E2)	0.327			
CD(E3)	0.317			
W1	0.36			
W2	0.33			
W3	0.31			
AG	0.064	0.161	0.196	0.328
DF	0.19			
FP	0.0005			

Table A3.52 Importance level and TE probability of each MC of compressor reduce quantity

MC probability	TE probability=0.012	Importance measure	Ranking of MCs
0.0051		0.423	1
0.0006		0.049	5
0.00054		0.044	7
0.0011		0.091	3
0.0028		0.232	2
0.0005		0.041	8
0.000006		0.0004	9
0.00055		0.0456	6
0.0009		0.0747	4

Appendix 4

Table A4.1 Aggregation of judgment of Expert 2 for RCO1 with respect to IC

WBEs				
1.Production packer	0	0	0.1	0.2
2.SCSSV	0.3	0.5	0.5	0.7
3.Completion string	0.1	0.25	0.25	0.4
SD(WBE12)	0.575			
SD(WBE13)	0.825			
SD(WBE23)	0.75			
AD(WBE1)	0.7			
AD(WBE2)	0.662			
AD(WBE3)	0.787			
RDA(WBE1)	0.325			
RDA(WBE2)	0.308			
RDA(WBE3)	0.366			
CD(WBE1)	0.325			
CD(WBE2)	0.308			
CD(WBE3)	0.366			
Aggregation of Ex1	0.129	0.245	0.2781	0.427

Table A4.2 Aggregation of judgment of Expert 3 for RCO1 with respect to IC

WBEs				
1.Production packer	0.1	0.25	0.25	0.4
2.SCSSV	0.6	0.75	0.75	0.9
3.Completion string	0.1	0.25	0.25	0.4
SD(WBE12)	0.5			
SD(WBE13)	1			
SD(WBE23)	0.5			
AD(WBE1)	0.75			
AD(WBE2)	0.5			
AD(WBE3)	0.75			
RDA(WBE1)	0.375			
RDA(WBE2)	0.25			
RDA(WBE3)	0.375			
CD(WBE1)	0.375			
CD(WBE2)	0.25			
CD(WBE3)	0.375			
Aggregation of Ex1	0.225	0.375	0.375	0.525

Table A4.3 Aggregation of judgment of Expert 1 for RCO2 with respect to IC

WBEs				
1.Production packer	0.1	0.25	0.25	0.4
2.SCSSV	0.3	0.5	0.5	0.7
3.Completion string	0.3	0.5	0.5	0.7
SD(WBE12)	0.75			
SD(WBE13)	0.75			
SD(WBE23)	1			
AD(WBE1)	0.75			
AD(WBE2)	0.875			
AD(WBE3)	0.875			
RDA(WBE1)	0.3			
RDA(WBE2)	0.35			
RDA(WBE3)	0.35			
CD(WBE1)	0.3			
CD(WBE2)	0.35			
CD(WBE3)	0.35			
Aggregation of Ex1	0.24	0.425	0.425	0.61

Table A4.4 Aggregation of judgment of Expert 2 for RCO2 with respect to IC

WBEs				
1.Production packer	0	0	0.1	0.2
2.SCSSV	0.3	0.5	0.5	0.7
3.Completion string	0.1	0.25	0.25	0.4
SD(WBE12)	0.575			
SD(WBE13)	0.825			
SD(WBE23)	0.75			
AD(WBE1)	0.7			
AD(WBE2)	0.6625			
AD(WBE3)	0.7875			
RDA(WBE1)	0.325581			
RDA(WBE2)	0.30814			
RDA(WBE3)	0.366279			
CD(WBE1)	0.325581			
CD(WBE2)	0.30814			
CD(WBE3)	0.366279			
Aggregation of Ex1	0.12907	0.24564	0.278198	0.427326

Table A4.5 Aggregation of judgment of Expert 3 for RCO2 with respect to IC

WBEs				
1.Production packer	0.1	0.25	0.25	0.4
2.SCSSV	0.6	0.75	0.75	0.9
3.Completion string	0.6	0.75	0.75	0.9
SD(WBE12)	0.5			
SD(WBE13)	0.5			
SD(WBE23)	1			
AD(WBE1)	0.5			
AD(WBE2)	0.75			
AD(WBE3)	0.75			
RDA(WBE1)	0.25			
RDA(WBE2)	0.375			
RDA(WBE3)	0.375			
CD(WBE1)	0.25			
CD(WBE2)	0.375			
CD(WBE3)	0.375			
Aggregation of Ex1	0.475	0.625	0.625	0.775

Table A4.6 Aggregation of three experts' rating with respect to IC

Expert 1 (E1)		0.24	0.425	0.425	0.61
Expert 2 (E2)		0.13	0.245	0.278	0.427
Expert 3 (E3)		0.475	0.625	0.625	0.775
SD (E12)	0.845				
SD (E13)	0.8				
SD (E23)	0.645				
AD (E1)	0.822				
AD(E2)	0.745				
AD(E3)	0.727				
RDA(E1)	0.359				
RDA(E2)	0.325				
RDA(E3)	0.315				
CD(E1)	0.364				
CD(E2)	0.332				
CD(E3)	0.302				
Weight of expert 1		0.37			
Weight of expert 2		0.34			
Weight of expert 3		0.29			
Aggregation for RCO1		0.271	0.426	0.44	0.6

Table A4.7 RCO2 aggregation with considering CON

Expert 1 (E1)	0.6	0.75	0.75	0.9
Expert 2 (E2)	0.6	0.75	0.75	0.9
Expert 3 (E3)	0.6	0.75	0.75	0.9
SD (E12) 1				
SD (E13) 1				
SD (E23) 1				
AD (E1) 1				
AD(E2) 1				
AD(E3) 1				
RDA(E1) 0.333				
RDA(E2) 0.333				
RDA(E3) 0.333				
CD(E1) 0.351				
CD(E2) 0.336				
CD(E3) 0.311				
Weight of expert 1	0.37			
Weight of expert 2	0.34			
Weight of expert 3	0.29			
Aggregation for RCO1	0.6	0.75	0.75	0.9

Table A4.8 Aggregation of the three experts' judgment on REL for RCO2

Expert 1 (E1)	0.108	0.281	0.281	0.567
Expert 2 (E2)	0.108	0.281	0.281	0.567
Expert 3 (E3)	0.144	0.337	0.375	0.63
SD (E12) 1				
SD (E13) 0.937				
SD (E23) 0.937				
AD (E1) 0.968				
AD(E2) 0.968				
AD(E3) 0.937				
RDA(E1) 0.336				
RDA(E2) 0.336				
RDA(E3) 0.326				
CD(E1) 0.353				
CD(E2) 0.338				
CD(E3) 0.308				
Weight of expert 1	0.37			
Weight of expert 2	0.34			
Weight of expert 3	0.29			
Aggregation for RCO1	0.12	0.29	0.31	0.59

Table A4.9 Aggregation of judgment of Expert 1 for RCO3with respect to IC

WBEs				
1.Casing cement	0.1	0.25	0.25	0.4
2.Casing	0.1	0.25	0.25	0.4
3.Tubing hanger	0	0	0.1	0.2
4. Well head	0.1	0.25	0.25	0.4
5. Production tree	0.1	0.25	0.25	0.4
6. Annulus valve	0.1	0.25	0.25	0.4
SD(WBE12)	1			
SD(WBE13)	0.825			
SD(WBE14)	1			
SD(WBE15)	1			
SD(WBE16)	1			
SD(WBE23)	0.825			
SD(WBE24)	1			
SD(WBE25)	1			
SD(WBE26)	1			
SD(WBE34)	0.825			
SD(WBE35)	0.825			
SD(WBE36)	0.825			
SD(WBE45)	1			
SD(WBE46)	1			
SD(WBE56)	1			
AD(WBE1)	0.965			
AD(WBE2)	0.965			
AD(WBE3)	0.825			
AD(WBE4)	0.965			
AD(WBE5)	0.965			
AD(WBE6)	0.965			
RDA(WBE1)	0.170796			
RDA(WBE2)	0.170796			
RDA(WBE3)	0.146018			
RDA(WBE4)	0.170796			
RDA(WBE5)	0.170796			
RDA(WBE6)	0.170796			
Aggregation of ex1 IC	0.085398	0.213496	0.228097	0.370796

Table A4.10 Aggregation of judgment of Expert 2 for RCO3with respect to IC

WBEs				
1.Casing cement	0	0	0.1	0.2
2.Casing	0.1	0.25	0.25	0.4
3.Tubing hanger	0.1	0.25	0.25	0.4
4. Well head	0.3	0.5	0.5	0.7
5. Production tree	0.1	0.25	0.25	0.4
6. Annulus valve	0	0	0.1	0.2
SD(WBE12)	0.825			
SD(WBE13)	0.825			
SD(WBE14)	0.575			
SD(WBE15)	0.825			
SD(WBE16)	1			
SD(WBE23)	1			
SD(WBE24)	0.75			
SD(WBE25)	1			
SD(WBE26)	0.825			
SD(WBE34)	0.75			
SD(WBE35)	1			
SD(WBE36)	0.825			
SD(WBE45)	0.75			
SD(WBE46)	0.575			
SD(WBE56)	0.825			
AD(WBE1)	0.81			
AD(WBE2)	0.88			
AD(WBE3)	0.88			
AD(WBE4)	0.68			
AD(WBE5)	0.88			
AD(WBE6)	0.81			
RDA(WBE1)	0.163968			
RDA(WBE2)	0.178138			
RDA(WBE3)	0.178138			
RDA(WBE4)	0.137652			
RDA(WBE5)	0.178138			
RDA(WBE6)	0.163968			
Aggregation of ex1 IC	0.094737	0.202429	0.235223	0.375709

Table A4.11 Aggregation of judgment of Expert 3 for RCO3with respect to IC

WBEs				
1.Casing cement	0.1	0.25	0.25	0.4
2.Casing	0	0	0.1	0.2
3.Tubing hanger	0.1	0.25	0.25	0.4
4. Well head	0.1	0.25	0.25	0.4
5. Production tree	0.3	0.5	0.5	0.7
6. Annulus valve	0.1	0.25	0.25	0.4
SD(WBE12)	0.825			
SD(WBE13)	1			
SD(WBE14)	1			
SD(WBE15)	0.75			
SD(WBE16)	1			
SD(WBE23)	0.825			
SD(WBE24)	0.825			
SD(WBE25)	0.575			
SD(WBE26)	0.825			
SD(WBE34)	1			
SD(WBE35)	0.75			
SD(WBE36)	1			
SD(WBE45)	0.75			
SD(WBE46)	1			
SD(WBE56)	0.75			
AD(WBE1)	0.915			
AD(WBE2)	0.775			
AD(WBE3)	0.915			
AD(WBE4)	0.915			
AD(WBE5)	0.715			
AD(WBE6)	0.915			
RDA(WBE1)	0.17767			
RDA(WBE2)	0.150485			
RDA(WBE3)	0.17767			
RDA(WBE4)	0.17767			
RDA(WBE5)	0.138835			
RDA(WBE6)	0.17767			
Aggregation of ex1 IC	0.112718	0.247087	0.262136	0.411553

Table A4.12 Aggregation of three experts' rating with respect to IC

Expert 1 (E1)	0.16	0.325	0.325	0.49
Expert 2 (E2)	0.13	0.245	0.278	0.427
Expert 3 (E3)	0.225	0.375	0.375	0.525
SD (E12) 0.945 SD (E13) 0.95 SD (E23) 0.895 AD (E1) 0.947 AD(E2) 0.92 AD(E3) 0.922 RDA(E1) 0.339 RDA(E2) 0.329 RDA(E3) 0.330 CD(E1) 0.354 CD(E2) 0.334 CD(E3) 0.310				
Weight of expert 1	0.37			
Weight of expert 2	0.34			
Weight of expert 3	0.29			
Aggregation for RCO1	0.17	0.314	0.325	0.48

Table A4.13 Aggregation of the three experts' judgment REL for RCO3

Expert 1 (E1)	0.147	0.369	0.562	0.81
Expert 2 (E2)	0.196	0.442	0.75	0.9
Expert 3 (E3)	0.147	0.369	0.562	0.81
SD (E12) 0.9 SD (E13) 1 SD (E23) 0.9 AD (E1) 0.95 AD(E2) 0.9 AD(E3) 0.95 RDA(E1) 0.339 RDA(E2) 0.321 RDA(E3) 0.339 CD(E1) 0.354 CD(E2) 0.330 CD(E3) 0.314				
Weight of expert 1	0.37			
Weight of expert 2	0.34			
Weight of expert 3	0.29			
Aggregation for RCO1	0.16	0.393	0.624	0.84

Table A4.14 RCO3 aggregation with considering CON

Expert 1 (E1)		0.6	0.75	0.75	0.9
Expert 2 (E2)		0.6	0.75	0.75	0.9
Expert 3 (E3)		0.6	0.75	0.75	0.9
SD (E12)	1				
SD (E13)	1				
SD (E23)	1				
AD (E1)	1				
AD(E2)	1				
AD(E3)	1				
RDA(E1)	0.333				
RDA(E2)	0.333				
RDA(E3)	0.333				
CD(E1)	0.351				
CD(E2)	0.336				
CD(E3)	0.311				
Weight of expert 1		0.37			
Weight of expert 2		0.34			
Weight of expert 3		0.29			
Aggregation for RCO1		0.6	0.75	0.75	0.9

Table A4.15 Aggregation of judgment of Expert 1 for RCO4 with respect to IC

WBEs				
1.Casing cement	0.3	0.5	0.5	0.7
2.Casing	0.1	0.25	0.25	0.4
3.Tubing hanger	0.3	0.5	0.5	0.7
4. Well head	0.3	0.5	0.5	0.7
5. Production tree	0.6	0.75	0.75	0.9
6. Annulus valve	0.3	0.5	0.5	0.7
SD(WBE12)	0.75			
SD(WBE13)	1			
SD(WBE14)	1			
SD(WBE15)	0.75			
SD(WBE16)	1			
SD(WBE23)	0.75			
SD(WBE24)	0.75			
SD(WBE25)	0.5			
SD(WBE26)	0.75			
SD(WBE34)	1			
SD(WBE35)	0.75			
SD(WBE36)	1			
SD(WBE45)	0.75			
SD(WBE46)	1			
SD(WBE56)	0.75			
AD(WBE1)	0.9			
AD(WBE2)	0.7			
AD(WBE3)	0.9			

AD(WBE4)	0.9			
AD(WBE5)	0.7			
AD(WBE6)	0.9			
RDA(WBE1)	0.18			
RDA(WBE2)	0.14			
RDA(WBE3)	0.18			
RDA(WBE4)	0.18			
RDA(WBE5)	0.14			
RDA(WBE6)	0.18			
Aggregation of ex1 IC	0.314	0.5	0.5	0.686

Table A4.16 Aggregation of judgment of Expert 2 for RCO4 with respect to IC

WBEs				
1.Casing cement	0.1	0.25	0.25	0.4
2.Casing	0.3	0.5	0.5	0.7
3.Tubing hanger	0.1	0.25	0.25	0.4
4. Well head	0.6	0.75	0.75	0.9
5. Production tree	0.6	0.75	0.75	0.9
6. Annulus valve	0.1	0.25	0.25	0.4
SD(WBE12)	0.75			
SD(WBE13)	1			
SD(WBE14)	0.5			
SD(WBE15)	0.5			
SD(WBE16)	1			
SD(WBE23)	0.75			
SD(WBE24)	0.75			
SD(WBE25)	0.75			
SD(WBE26)	0.75			
SD(WBE34)	0.5			
SD(WBE35)	0.5			
SD(WBE36)	1			
SD(WBE45)	1			
SD(WBE46)	0.5			
SD(WBE56)	0.5			
AD(WBE1)	0.75			
AD(WBE2)	0.75			
AD(WBE3)	0.75			
AD(WBE4)	0.65			
AD(WBE5)	0.65			
AD(WBE6)	0.75			
RDA(WBE1)	0.174419			
RDA(WBE2)	0.174419			
RDA(WBE3)	0.174419			
RDA(WBE4)	0.151163			
RDA(WBE5)	0.151163			
RDA(WBE6)	0.174419			
Aggregation of ex1 IC	0.286	0.444	0.444	0.603

Table A4.17 Aggregation of judgment of Expert 3 for RCO4 with respect to IC

WBEs				
1.Casing cement	0.1	0.25	0.25	0.4
2.Casing	0.3	0.5	0.5	0.7
3.Tubing hanger	0.3	0.5	0.5	0.7
4. Well head	0.6	0.75	0.75	0.9
5. Production tree	0.6	0.75	0.75	0.9
6. Annulus valve	0	0	0.1	0.2
SD(WBE12)	0.75			
SD(WBE13)	0.75			
SD(WBE14)	0.5			
SD(WBE15)	0.5			
SD(WBE16)	0.825			
SD(WBE23)	1			
SD(WBE24)	0.75			
SD(WBE25)	0.75			
SD(WBE26)	0.575			
SD(WBE34)	0.75			
SD(WBE35)	0.75			
SD(WBE36)	0.575			
SD(WBE45)	1			
SD(WBE46)	0.325			
SD(WBE56)	0.325			
AD(WBE1)	0.665			
AD(WBE2)	0.765			
AD(WBE3)	0.765			
AD(WBE4)	0.665			
AD(WBE5)	0.665			
AD(WBE6)	0.525			
RDA(WBE1)	0.164198			
RDA(WBE2)	0.188889			
RDA(WBE3)	0.188889			
RDA(WBE4)	0.164198			
RDA(WBE5)	0.164198			
RDA(WBE6)	0.12963			
Aggregation of ex1 IC	0.326	0.476	0.489	0.651

Table A4.18 Aggregation of three experts' rating with respect to IC

Expert 1 (E1)	0.314	0.5	0.5	0.686
Expert 2 (E2)	0.331	0.5	0.5	0.667
Expert 3 (E3)	0.326	0.476	0.489	0.652
SD (E12) 0.999 SD (E13) 0.985 SD (E23) 0.986 AD (E1) 0.992 AD(E2) 0.992 AD(E3) 0.986 RDA(E1) 0.334 RDA(E2) 0.334 RDA(E3) 0.331 CD(E1) 0.352 CD(E2) 0.337 CD(E3) 0.310				
Weight of expert 1	0.37			
Weight of expert 2	0.34			
Weight of expert 3	0.29			
Aggregation for RCO1	0.323	0.49	0.5	0.67

Table A4.19 RCO4 aggregation with considering CON

Expert 1 (E1)	0.6	0.75	0.75	0.9
Expert 2 (E2)	0.6	0.75	0.75	0.9
Expert 3 (E3)	0.8	0.9	1	1
SD (E12) 1 SD (E13) 0.825 SD (E23) 0.825 AD (E1) 0.912 AD(E2) 0.912 AD(E3) 0.825 RDA(E1) 0.344 RDA(E2) 0.344 RDA(E3) 0.311 CD(E1) 0.357 CD(E2) 0.342 CD(E3) 0.300				
Weight of expert 1	0.37			
Weight of expert 2	0.34			
Weight of expert 3	0.29			
Aggregation for RCO1	0.660	0.795	0.825	0.930

Table A4.20 Aggregation of the three experts' judgment on REL for RCO4

Expert 1 (E1)		0.041	0.17	0.21	0.364
Expert 2 (E2)		0.041	0.17	0.21	0.364
Expert 3 (E3)		0.104	0.256	0.316	0.656
SD (E12)	1				
SD (E13)	0.863				
SD (E23)	0.863				
AD (E1)	0.931				
AD(E2)	0.931				
AD(E3)	0.863				
RDA(E1)	0.341				
RDA(E2)	0.341				
RDA(E3)	0.316				
CD(E1)	0.355				
CD(E2)	0.340				
CD(E3)	0.303				
Weight of expert 1		0.37			
Weight of expert 2		0.34			
Weight of expert 3		0.29			
Aggregation for RCO1		0.06	0.2	0.24	0.45

Appendix 5

1) Wanted and unwanted input

A well barrier should withstand the environment and maximum anticipated differential pressure it may be exposed to over time (NORSOK D-010). Changes in input during the well life must be frequently assessed (change in well fluid composition, excessive pressure, scale, particles in the flow, etc.). It is also important to consider unwanted input. For example, failure of the primary well barrier might result in high pressure on a secondary well barrier.

2) Wanted and unwanted output

The acceptable leak rate shall be zero, unless specified. In situations where the function of the well barrier is weakened, but are still acceptable should be defined (NORSOK D-010). A specific leak rate criterion for the SCSSV and the SCASV (Surface Controlled Annular Safety Valve) is specified in NORSOK D-010, which originates from API RP 14B. API RP 14B defines an acceptable leak rate, which is 15 SCF/min (~0.42 SCM/min) for gas, and400cm^3/min for liquids.

3) Boundary conditions

a) Two well barriers shall be available during all well activities and operations (NORSOK D-010 and industry practice). In addition NORSOK D-010 states that "*No single failure shall lead to uncontrolled outflow from the borehole/well to the external environment*".

b) *SSSV and SCASV valves should be placed minimum 50 m below seabed (NORSOK D-010).* The setting depth requirement makes the SCASV less vulnerable to external events. The setting depths of the SCSSV and the SCASV are primarily dictated by the pressure and temperature conditions in the well.

4) External threats (robustness)

The well barriers shall be designed, selected and/or constructed such that it can operate competently and withstand the environment for which it may be exposed to over time

(NORSOK D-010). In addition to long term environmental exposure, robustness include the ability to function under all accident conditions, and events like earthquake, fire, loss of energy supply, sabotage, falling loads, etc. should also be assessed.

5) System (availability)

a) The primary and secondary well barriers shall, to the extent possible, be independent of each other (NORSOK D-010). Independence makes the system more robust, and also increases the availability.

b) A SIL requirement to the well shut-in function should be established. It should also be controlled that the well shut-in function is able to fulfill this requirement in the well life.

6) Support

In the Facilities regulations (PSA, 2001b), section 47 it is stated that "*Well barriers shall be designed so that their performance can be verified.*" According to NORSOK D-010 "*The physical location and the integrity status of the well barrier shall be known at all times*". Verification of the performance of well barriers may be based on functional testing and condition monitoring (e.g., monitoring of changes in pressure). More specific, NORSOK D-010 states the following requirements to well barriers:

i) *A well barrier shall be leak tested, function tested or verified by other methods (NORSOK D-010).* NORSOK D-010 also requires that "*The SSSV, the production tree valves and the annulus valves shall be leak tested regularly*". Common practice on the Norwegian Continental Shelf (NCS) is to test valves every 6 months.

ii) *The pressure in all accessible annuli (A, B and/or C annuli) shall be monitored and maintained within minimum and maximum pressure range limits (NORSOK D-010).*

The requirements listed reflect the requirements in Norway. The list is not complete when looking at a specific well. However, the categorization above gives an overview of the most important requirements and how the requirements influence the system. The categorization may also be used to include additional requirements from other countries or from internal operator guidelines.