DESIGN FOR SAFETY FRAMEWORK FOR

OFFSHORE OIL AND GAS PLATFORMS

By

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Abstract

This main aim of this work is to develop a "design for safety" based risk assessment technique for the offshore platforms in order to facilitate decision making. This is achieved through detailed examination of related risks, and review of relevant literatures and traditional safety assessment methods leading to the development of a new knowledge-based risk assessment method (KBRAM) through the research methodology process.

The methodology involves detailed definition of the research aim and objectives, further literature review on risk analysis and the related topics of safety assessment and safety management systems. This process laid the foundation for the establishment of a framework for the integration of design for safety and fuzzy reasoning approach to model the risk assessment procedure for offshore platforms.

The research procedure requires collection of data which was obtained from the industry in this instance. The collection methods involve surveys visit interviews and questionnaires which together constitute vital information required for test running the model and conduct preliminary validation studies with regard to offshore platform risk assessment to enable provision reaching some conclusions.

The results obtained through testing of KBRAM using data collected from the industry show the determination of risk level classification has been improved compared to the one obtained using same data on the traditional fuzzy two-input parameter risk assessment method (TPRAM) due to the addition of a third parameter in the KBRAM.

In conclusion, the above result satisfy the research aim of facilitating decision-making process based on reduced cost of safety due to more efficient risk evaluations.

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CHAPTER 1

Introduction

This chapter gives the rundown of the main purpose of this research and presents a brief justification of the need for a comprehensive and structured methodology for the investigation and analysis of hazards associated with the offshore platforms. In this chapter also some historical developments related to safety management have been enumerated as a build up to the main research work. Further reviews include the safety of offshore oil and gas facilities, previous accident and incident reports, and governments post accident reports which are also highlighted in this chapter.

The issues identified through the reviews mentioned above led to changes in the way health and safety concerns are administered particularly in the industrialised nations. The Chapter also enumerated the basis for this research and concludes with summary of the thesis structure and its contents.

1.1 Background

Historically, the beginning of industrial revolution brought with it both social and economic consequences which have been the source of concern in many nations. These concerns generated a lot of clamour for changes which resulted in the formation of International labour organisation (ILO) in the year 1919. The organisation has among other functions, for example the responsibility for the compilation of systematic statistics of hazardous activities and their resultant consequences. This development clearly highlighted the enormous cost of accidents to society and provided the basis for the development of preventive strategies which made significant contribution towards improvement of health and safety legislations. The organisation produced the first worldwide projection of an annual estimate of about 264 million occupational accidents and fatalities of over 350,000 (Takala, 2006).

In 1988 an offshore facility named Piper Alpha (UK) suffered a monumental disaster which recorded a fatality of 167 deaths out of the 229 people on board. This accident necessitated the need for urgent changes in offshore health and safety management. Accordingly, these changes led to the establishment of offshore installation (Safety Case) regulations in the UK. The safety case is a written document which stipulates how a company demonstrates an effective safety management system is in place on any particular offshore installation. The responsibility for the monitoring of the implementation of this was assigned to Health and Safety Executive (HSE) in 1991. This study however, will concentrate on the safety implementation phase of the safety management system.

Safety analysis in this context can be described as the study of the consequences of engineering system failures in relation to possible harm to people and/or damage to environment or property including financial assets (HSE, 1999).

In consideration of the magnitude of the offshore safety problems, it is clear that safety studies require continuous efforts aimed at eliminating or reducing hazards (Lois *et al*, 2004). The task of safety analysis in this context will mainly concentrate on the prevention and/or mitigation or control of risks through the entire life of the project. This clearly resides within the concept of safety management.

However, it is pertinent to note that risk management is not about complete removal of risks but to encourage explicit decision making process, which will be used to mitigate the potential effects of certain risks and facilitate approvals for the project. The consensus of opinion among the experts on risk is unanimous in accepting the inadequacy of software only solutions to the risk management problem (Raftery, 1993).

Chapman (1991) described risk as a measure of exposure to the possibility of economic or financial loss or gain, physical damage or injury or delay as a consequence of the uncertainty associated with the pursuance of a particular course of action. This may necessitate the need for more innovations in risk management.

This management will involve risk analysis as a means of encouraging innovative deployment of various techniques not only to conduct the systematic analysis procedures but also to deal with the uncertainty problems relating to the risk information. This process involves the risk identification, evaluation, control, recommendation, and implementation. The various techniques for risk assessment based on recent experiences brought more significant gains as well as offer more benefits to the industry in the long term (Cooper & Chapman, 1987).

In the light of the above development risk analysis techniques are increasingly being deployed to assess risk and minimise losses in several industries such as railways, nuclear, chemical processing, oil & gas etc.

These tremendous benefits brought about by risk management efforts can be summarised as follows (An, 2003a):

- Resulted in substantial reduction in the exposure to risk.

- Introduced proactive risk response mechanism through planning.
- Established the foundation for making explicit decisions on project.
- Provided clearer opportunity for identification of peculiar risks associated with any given project.
- Explored the full potentials of risk personnel based on skills and experience.
- Encouraged production of high quality documentation on project risks at corporate level for continuous update and improvement.
- Provided better opportunities for collation of reliable data for further research and improvement in the area of analysis of risks.

In conducting this review, it is considered that risk is inherent in all oil and gas development projects, coupled with other influential factors such as unstable political or commercial landscape and planning. Risk may also be influenced by other factors such as size or complexity of the project, environment, execution period, and operative competence. Project targets are often not met despite the project manager's efforts aimed at lowering the risks due to other unpredictable events normally referred to as "force majeure" (Wang & Ruxton, 1998). This scenario prevents making general predictions thereby necessitating risks management approach for each individual project depending on its peculiarity.

Therefore, risk management has to be considered very vital for the successful project delivery, though often constrained of inadequate work processes and software tools. An overall understanding of the different risk factors and how they affect the project necessitate the need to clearly define project performance goals as critical factors for the achievement of successful project management and decision-making.

Project Risk Management (PRM) involves a process of systematic approach for analysing and managing threats as well as project opportunities that are likely to increase the possibilities of attainment of typical project objectives such as cost, time schedule, and operational availability right from the early design stages. The PRM techniques will be used to facilitate the identification of major risk drivers and their effects on the project objectives. This process offers great opportunity for the development of suitable risk strategies and plan of action required to successfully manage and mitigate project potentials (Wang & Ruxton, 1997).

Following the above, the choice between these techniques which depends on the quality of the information available and the kind of decisions PRM supports. Frequent use of PRM is typically based on using risk parameters such as the probability of failure event and its consequence, which account for threats and opportunities. The high level of uncertainty usually related with the information pose serious challenge to the safety analyst thereby necessitating the need to be more proactive in seeking direct decision support through probabilistic analyses or other alternatives especially in offshore developments.

Offshore oil and gas development projects are characterised by large investments, tight time schedules and the evolving technology through sometimes unproven conditions. These challenges result in higher risk exposure and along with which come more opportunities to be exploited in terms of safety management (Khan, 2002b).

1.2 Offshore Project Challenges

The design and installation of offshore platforms involve a very complicated process with attendant risks to people, environment and property or economic assets. The traditional methods of carrying out risk assessment during installation and construction or after occurrence of accidents proved to be costly and often saddled with lack of flexibility for alternative remedial options (Khan, 2002b).

It also must be noted that offshore field development is a complex activity involving uncertainties from a wide range of sources. These uncertainties often comprise both potentially hazardous events and their attendant undesirable consequences in one hand and on the other presents opportunities for desired consequences or success. The task of managing these uncertainties from early stages is the main objective of safe design concept (Cleveland & King, 1983).

The above referred uncertainties may come from a wide range of areas and disciplines, which can be broadly grouped into the followings (Umar *et al*, 2006):

- Technical
- Financial
- Organisational
- Contract and/or procurement
- Sub-contract
- Political and/or cultural

It is obvious that, all of the above listed factors will contribute to the overall uncertainty in the planning, execution and operation of the project. The project objectives, or the measure of project success or failure, are often defined in terms of cost, time schedule, and technical performance. In response to these challenges, safety analysis must be tailored towards the attainment of these project objectives through the provision of systematic approach for analysing, controlling, and documenting identified threats and opportunities both during planning and execution of the project. Safety assessment can be carried out at various phases of an offshore field development project, such as the feasibility study phase, concept study phase, pre-engineering phase, detailed engineering phase, construction phase and commissioning phase (Umar *et al,* 2006). The major inherent safety challenges confronting the offshore development projects are as listed below:

- Blow out
- Fire
- Explosion
- Falling objects
- Ship or helicopter impact
- Earthquakes
- Extreme weather

It is clear that the above listed challenges suggest the need for continuous efforts to evolve more systematic approaches or techniques for controlling and monitoring safety, particularly from the very early development stages through design process (Gupta & Edwards, 2002). Sequel to the aforementioned, this research project will be dedicated to the development of a new proposed risk assessment model for offshore platforms based on the concept of "design for safety" and principles of fuzzy reasoning approach in order to deal with the imprecise safety information and other associated complex risk factors.

1.3 Research Basis

The initial question, which stimulates the idea of this work, is expressed as: - is there any need for another approach for safety provision in the design of offshore platforms? The hypothesis that whether the new approach will make any difference or resultant improvement in offshore platform safety management. The answer is yes, as any simplistic approach built on some well tested methods would make more meaningful impact so long as it is not based on common sense.

However, the answer can never be that simple when one considers the tremendous efforts made in this area. In the work of Wang & Ruxton, (1997) it was stated that, in recent years, design engineers and safety researchers have continually developed and applied quantitative safety techniques, but almost all have not received acceptance enough to encourage their wider application in order to guarantee ultimate solutions to safety based decisions during the design process. However, these techniques succeeded by offering better opportunities for further development of more objective and efficient safety analysis methods that facilitated the efforts of integrating safety features into the design process from the initial stages (Umar *et al*, 2006). Some constraints or difficulties associated with this process must also be highlighted which include;

- Insufficient data in most cases while in some cases it is difficult to obtain. This results in having very poor statistical accuracy.
- It is extremely difficult to carry out "design for safety" produce or use a single mathematical model for a project of such magnitude as an offshore platform.
- The decision making process is made so difficult due to the combination of the complex task of defining the scope or extent of "design for safety" at the early stages, as well as the enormity of work and the associated cost of safety quantification process.

- The high level of uncertainty associated with the quantification of effects and consequences of hazard which constitute some difficulties to the “design for safety” process.
- The quantification of risks involves significant number of assumptions, estimations, judgements, and opinions which often require the involvement of very skilful safety analyst to interpret the results.
- It is also extremely difficult to set up absolute criteria for safety acceptability as safety is only a part of the important requirements for the appraisal of the acceptability of an industrial activity.

1.4 Structure of the Thesis

Chapter 1:- The need for continuous efforts aimed at the development of more comprehensive and structured methods for the investigation and analysis of hazards associated with offshore platforms is highlighted and some historical development related to safety management systems also discussed. The industrial reports on previous accidents and incidents, and governmental reports are also reviewed in this Chapter. The discussion concludes with outline of the whole thesis structure of thesis.

Chapter 2:- This Chapter presents the concepts of safety and safety systems, as well as their applications into more complex approaches, as per the current safety management system. The current safety management system was introduced and, its elements and components also discussed. In efforts to achieve a comprehensive review relative to the relevance of the topic, various safety assessment methods are discussed enumerating their strengths or benefit to the current work and weaknesses leading to the identification of gaps in the safety of offshore platform which require further efforts. The Chapter also introduces the concept of design for safety which is considered very vital for the current study. The concept of "design for safety" is deployed in order to explore the possibilities of achieving the main objective of applying the principles of "design for safety" through the different design stages for offshore platforms in order to facilitate decision-making process.

Chapter 3:- The framework for the methodology adopted in this research is discussed in details in this Chapter. This framework involves giving detailed definition of the research aim and objectives, review of some relevant literature and conducting broader discussions leading to identification of the gaps in the area of dealing with safety challenges associated with development of offshore platforms. The Chapter enumerated further highlights on the links between the research objectives and, how they are achieved and demonstrated through different parts of this report.

Chapter 4:- In this chapter, the concepts of offshore platform safe design approach is enumerated and the design processes also reviewed in efforts to establish foundation for the proposed design for safety framework. Further highlights include how a modified "design for safety" framework has been developed and proposed for the achievement of safe design of offshore platforms. This modification is intended to form the basis for the development of a safety assessment method to be employed in the safety modelling process for offshore platforms.

Chapter 5: Following the review of design for safety in Chapter 4, this chapter focuses on the second vital part of what form the basis for safety modelling for offshore platforms. This vital part is fuzzy reasoning approach (FRA) and its fundamental principles which are enumerated and discussed. Therefore, in this study FRA is considered as the main thrust of the modelling process due to its comparative advantage over other methods in terms of effective treatment of inherent uncertainties usually associated with risk information. The Chapter concludes the framework for the development of an integrated design for safety-FRA based risk assessment method referred in this work as knowledge-based risk assessment method (KBRAM) for safety assessment through the development stages for offshore platform.

Chapter 6: This Chapter presents the development of (KBRAM) and its application procedures. This method begins with the establishment of foundation based on requirements, which the traditional safety assessment methods cannot adequately process any information that is deemed to be vague or lacking details required in terms of both quality and quantity at this stage. The KBRAM system framework developmental approach is enumerated and the methodology is also outlined. Demonstration of the KBRAM procedure is conducted with step by step illustrations using examples to interpret the mathematical equations throughout the Chapter. The Chapter concludes with discussion on the method's main attributes and innovations.

Chapter 7: This Chapter reports on tests and illustrations of the performance of KBRAM, and its preliminary validation studies. The Chapter begins with demonstration of how the method is used to process safety information using real data collected from the industry with particular emphasis on offshore processing unit which is considered to be a very important and hazardous part of an offshore oil & gas platform. This unit is made up of six sub- systems each consisting of different components ranging between 15 and 21.

The proposed KBRAM approach is applied to the six sub-systems of the offshore process unit that consists of two separators (Oil & Condensate), two compressors (1 & 2), flash drum, and drier. Comparative study of two results based on the same principles and data with the only difference being an additional input parameter in the case of KBRAM as against the typical two-parameter risk assessment method (TPRAM) which basically has two input parameters is presented. The Chapter concludes with discussions and recommendations of appropriate safety measures for each of sub-systems based on the analyses of the results mentioned above.

Chapter 8: This Chapter enumerated the conclusions based on the compilation of the progressive discussions from Chapters 1 to 7 demonstrating how the research aim and objectives are achieved through the research methodology framework adopted in this study. The Chapter also highlighted recommendations for the improvement in the related areas currently militating against smooth conduct of research within the industry. It concludes with future works for exploring other possibilities or improvement in managing uncertainties especially regarding experts' opinion or knowledge.

CHAPTER 2

Concept of Safety Management

2.1 Introduction

This Chapter is intended to provide an extensive literature review on how safety concept and system have been used to develop several complex safety management approaches to facilitate decision making process. Current safety management systems and models are introduced, and their processes are described and discussed in the following sections.

As mentioned above, there are many forms of safety management systems but the most commonly used ones are (i) the traditional method of safety and, (ii) the proactive methods and philosophies of quality in conjunction with safety.

Safety professionals in companies adopting the traditional method of safety directly ensure that workers comply with the expected company safety standards and regulations as well as enforce laws and government regulations. They are informed on new regulations, devoted to impose rules and regulations to their employees, carry out inspections, audit the system, direct investigations of accidents and injuries, and establish recommendations in order to prevent accidents and injuries in future. For the safety professionals, adhering to this concept means modifying the behaviour of the workers, motivating them, and using prizes and incentives to help them work in a safer way. Rewards are given only to those workers or departments that meet the pre-set safety objectives (Council, 1989).

The traditional safety management programmes do not always improve the results of safety because they are centered exclusively on the technical requirements and achievement of shortterm results. It has been observed that organisations adopting the traditional safety management only respond after occurrence of accidents or injuries.

Another shortcoming of the traditional safety management program is that the program is isolated and most times disconnected with the rest of the functions of an organisation. The common elements of traditional safety management structure include: safety director, safety committee meetings relating to safety, list of rules pertaining to safety, posting of slogans, posters, and programs of safety incentives. The responsibility of the safety program falls on the safety director, who occupies a position inside the organization of the company and, in many cases, does not have the authority to make changes (Council, 1989).

A proactive system centered on taking a pre-emptive approach is more effective than the one that continually analyse accidents after they happen in order to generate data on which to base improvements. Prevention is based on established rules, regulations, and safety instructions, but the mere publication of those rules and regulations in a safety manual is not enough for their effective implementation. Only when all personnel work in accordance with the safety norms and the established instructions will the company have safe practices (Petersen, 1988).

The ten obligations of safety management as defined by Petersen (1978) express the way of deviating from traditional safety management through adoption of new obligations within the company:

- Progress is not measured by injury ratios.
- Safety becomes a system, more than a program.

- Statistical techniques drive the efforts of continuous improvement.
- The investigation of accidents and injuries is renewed or is eliminated.
- Technical principles and tools for the statistical control of the process are used.
- Emphasis is placed on improving the system.
- Benefits are provided for people that discover illegal situations.
- The participation of workers in the resolution of problems and making decisions is formalised.
- Ergonomic well-being is projected inside the place of work.
- The traps within the system that cause human errors are eliminated.

2.2 Definitions of Safety Management

Safety management can be defined in several ways, Cox and Tait (1991) defined it as "the process whereby informed decision are taken to meet safety criteria", in other words safety management is "the management process deployed to achieve a state of freedom from the unacceptable risks of personal harm or loss or damage". Hazards or failure investigation methods are fundamental to the process of system safety management.

The primary aim of safety management is to provide intervention mechanism in the process causing accident by breaking its chain (HSC, 1993). Safety management involves among others detection and/or prevention of inherent failures in the process of hazard identification, risk assessment, control, and monitoring (Gupta & Edwards, 2002).

The above definition clearly defines safety management as an integral part of the safety management system dealing with decision making and implementation of safety control measures.

Decision making process involving safety is based on a systematic identification and assessment of risks with the pre-defined risk acceptability and tolerability level. Reduction and elimination of risk strategies are generally based on cost-benefit analysis with other requirements such as legal, social, and moral values playing significant role (HSC, 1993).

2.3 Historical Perspective of Safety Management

Though safety management concepts described above are relatively current, the safety at work literature can be traced back long before now. In 1920's Herbert Heinrich one of the early thinkers of safety in the United States conducted a study of the direct and indirect costs of occupational accidents in which he identified the existence of a linear relationship and published a survey results on the relative frequency ratio of different types of accidents including a popular "accident pyramid" (Heinrich *et al*, 1980). Thereafter, various studies have been conducted to further establish relationship between serious and minor accidents. In 1997, a study by (HSE, 1997a) eventually confirmed and accepted the validity of the "pyramid" concept. According to this study, the pyramid effect and its use in preventive design strategies are still being debated.

Injuries caused by accidents lead to fatalities only when a number of contributing factors co exist simultaneously. Fatal accidents are just the tip of the iceberg, depending on the type of job, some 500-2,000 smaller injuries take place for each fatality (Takala, 2006).

It is a commonly agreed that there is little, if any, correlation between the occurrence of personal accidents and process accidents (Hale, 2001). The Texas City disaster has highlighted, yet again, how striving for a reduction in personal safety performance can completely miss all the requirements necessary to ensure process integrity. The lessons from Longford appeared not to have been learned. There has been the long-standing belief that the underlying causes of both personal and process safety problems are the same, but the hazards, and the defenses appropriate to manage them, differ considerably (Hale, 2003), so it is not surprising that the correlations will be low. Nevertheless, current evidence (Hudson, 2009) suggests that there is a level of commonality, but that it is at an abstract level, namely whether the organisation takes safety seriously or not. By this, it is probably only at the level of the organisational culture that there is a degree of common cause that can be identified (HSE, 1997b).

The culture of Texas City, one that accepted non-compliance at many levels, is one that underlies both personal and process incidents. The lack of correlation may be due to a concentration on the immediate causes and an inappropriate level of granularity. Another problem is that major process safety incidents are quite rare, while personal safety outcomes are more common. Even fatal accidents, typically due to transport or construction activities in high-hazard industries like oil and gas, are much more frequent than major process incidents that may, or may not, have personal consequences. There are a number of reasons for this, primarily due to the different types of hazards and the depth of defense provided (Hudson, 2009). With some of the personal safety hazards, defenses might be both minimal and primarily reliant upon the actions of the individual. Even if the failure rates of individual defenses are approximately the same for personal and process hazards, the occurrence of extreme outcomes will always be less frequent when there are more barriers and they are independent. With many personal safety hazards there are fewer barriers and they are often dependent upon the same individual (typically the victim).

The net result of the differences between personal and process safety means that concentrating upon the superficial factors, such as the immediate causes, makes personal safety much more salient and easier to understand. It is also easier to demonstrate commitment when responding vigorously to a personal injury rather than waiting for a major process problem to arise. Part of the discussion about indicators represents an attempt to find appropriate levels of description that provide more similar frequencies or level of causal abstraction of indicator events or states. Therefore, it may select responses to such indicator events, preferably with corrective actions as well as uncovering failures that may be causally equivalent but due to the greater depth of defense, it may be less likely to have led to severe outcomes in the case of process safety events (Hudson, 2009).

The 1960's witnessed the emergence of loss control prevention theories, precisely, loss prevention approach was developed in 1960 in the UK by the Institute of Chemical Engineers, which is long before the American Institute of Chemical Engineers initiated an annual series of symposia on "loss prevention" in 1967 (Lees, 1980). Following the Flixborough disaster in 1974, research efforts became more intensified as evident in the work of Frank Lees, in which loss prevention was clearly identified as an integral part of the management system and hazard quantification as part of the process of loss prevention which depends on the use of reliability engineering (Lees, 1980, Lees, 1996). This approach though developed in the process industry for the identification, assessment and control of hazards, its principles is applicable in other industrial activities.

In the 1970's, the use of "safety system" and "safety engineering system" in the industry became more popular through the work of such prominent researchers as Bertalanffy, (1971), Johnson, (1973, 1980), Brown, (1976), Hammer, (1972, 1980, 1989), Peterson, (1978, 1988) etc. Although most of the above mentioned works concentrated on the engineering aspect of the subject, however, Brown (1976) provided some justifications that some of the contemporary colleagues started transforming system concepts into reality.

Since then most of the safety management techniques have been applied to "system engineering" aspects such as product safety in the design of manufacturing processes. During this period, Brown (1976) stated that safety engineers saddled with the management of safety were drawn from the ranks, operations research, industrial engineering and other disciplines.

From the late 1970's and early 1980's most safety literature concentrated mainly on control of hazards and human behaviour using technology complimented by cost elements. Industry top managers devoted more attention to budget and compliance with legal and regulatory requirements.

However, several major accidents such as Chernobyl, Piper Alpha etc revealed other possible causes than the traditional engineering failure and operation including human errors. The industry recognises the need to involve the entire structure dealing with safety matters. Accordingly, the dynamics of safety literature begin to involve top management in managing all safety matters as a measure of Health and Safety (H&S) compliance within any particular organisations.

The accidents mentioned above, brought about increase social awareness and ethical concerns which possibly encouraged governments and policy makers to embrace a more proactive and leading role in managing safety. In the UK, for instance, the first government action came in Robens report (1972), which recommended that safety management must be the responsibility of all stakeholders if successes are to be recorded in accident preventions.

The report (Robens, 1972) recommended “voluntary efforts” principles which provided a foundation for the statutory Health and Safety at work act 1974, and eventually lead to the establishment of Health and Safety Executive (HSE). This recommendation though voluntary at the time but changed the way safety management is seen in continental Europe, following this was the adoption of some of its basic principles by the European Council which became operational in 1989 (Council, 1989).

In 1971, in the USA, the Occupational Safety and Health Act (OSHA) became operative. These regulations placed “the responsibility for employers” safety, principally on employers (ISO 9000, 2000). The regulations also emphasise the importance of occupational H&S management as against previous concepts whereby occupational safety was considered along side industrial safety.

2.4 Safety Management Models

Most of the existing safety management models have been developed based on quality management system in line with BS EN ISO 9000, (2000) and environmental management systems in accordance with BS EN ISO 14001, (1996).

According to the HSE (1993) report, a proactive safety management must comprise of such key elements as hazard identification and assessment, established rules and procedures, training, and commitment to monitoring and mitigation of risks. This can only be achieved when properly guided by clear policy goals and objectives as well as dedicated action plan, other key factors include effective communication mechanism, defined structure and, clear and specific responsibilities.

In 1991, the United Kingdom developed its first formal and structural model of safety management system to guide organisational Health & Safety (H&S) in terms of achieving better improvement and implementation. This publication was further reviewed in 1997 (HSE-HSG 65) (HSE, 1997b) without any changes to the basic framework of the earlier edition. This UK HSE safety management model is in-line with the universal concepts comprising of the basic five key elements as illustrated in Figure 2.1. These key elements are briefly described as below.

2.4.1 Policy

The safety policy must be set up in a clear and formal way as to guarantee commitment and desire for continuous improvement. This policy must also give clear direction to reflect the organisational values and beliefs as well as demonstrate safety culture of the organisation.

2.4.2 Organisation

This involves definition of responsibilities and establishment of structures and processes to encourage the development of H&S in the organisation. Other key elements of organisation include effective communication and regular training of personnel for successful implementation of the policy.

2.4.3 Implementation

This is an integral part of planning dealing with prevention through the process of risks analysis and mitigation. Risk analysis covers hazard identification and assessments while risk mitigation is dedicated to control measures such as reduction or minimisation or elimination of hazard and/or its possible effects (consequences).

Implementation of safety policy must cover the entire organisation including but not limited to personnel, products, services, and environment etc.

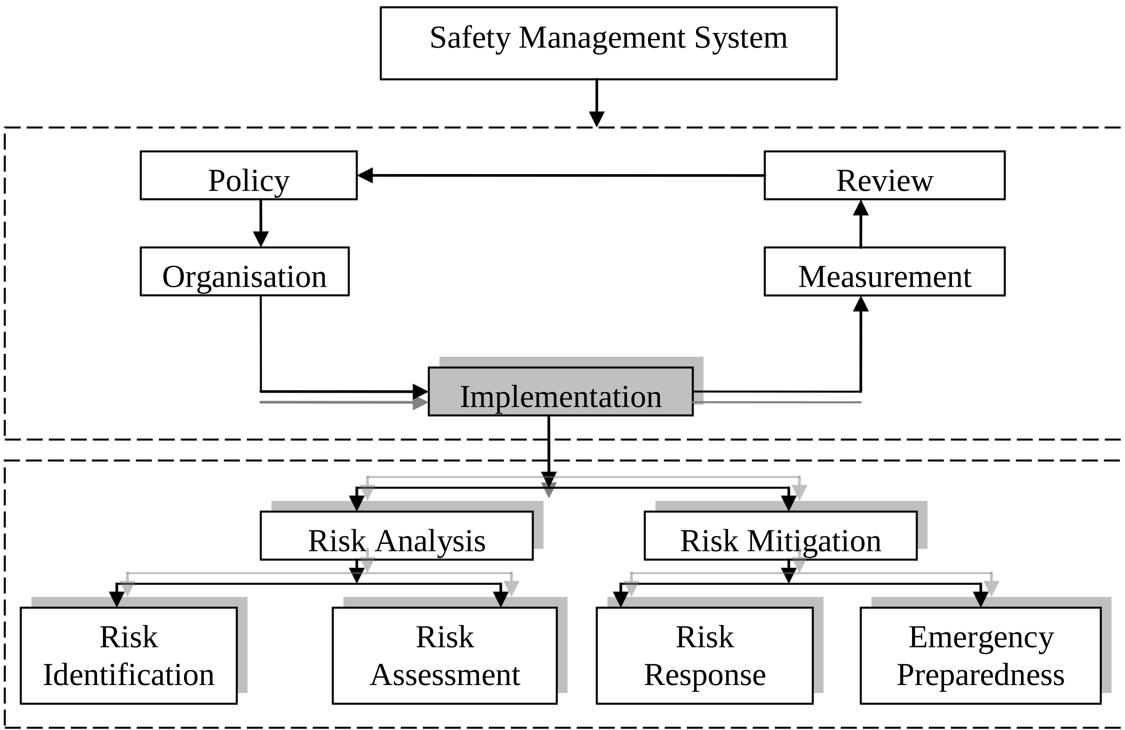

Fig. 2.1 Structure of Safety Management System

2.4.4 Measurement

Performance measurement is one of the most important means of assessing how the system is being managed and/or maintained as well as risks being controlled. The H&S established qualitative and quantitative indicators which when combined with benchmarking of organisational objectives and goals would provide necessary information regarding systems strength and weaknesses. This information is necessary in order to ensure that the management is well guided in decision making on safety improvement. This process involves active monitoring as a means of generating feedback on system's performance prior to the occurrence of any possible accident, incident, or ill health. Reactive monitoring is also deployed in order to monitor through analysis of accidents and other areas where H&S performances are found to be deficient.

2.4.5 Review

Reviewing the performance of the system is conducted through a comprehensive auditing process. This is a structured and systematic process of gathering independently verifiable information on the efficiency, effectiveness, and reliability of the entire system. The information gathered here would be used in providing the necessary means for mitigation based on the reviewed performances of all the components. The outcome of auditing process is applied to guarantee the establishment of i) appropriate management response, ii) adequate risk control provisions, and iii) appropriate precautionary measures.

2.4.6 Discussions

The HSE model described above has been adopted by most organisations in the UK as guidance to produce H&S management in line with the standard for best practice. However, despite the level of acceptance, the model has been criticised for lacking leadership, failure to inspire and non provision for rewards and sanctions. These limitations have been linked to failure by many organisations to effectively implement the system. It has also been contemplated that, there is a possibility that further inclusion of these factors may complicate the model and make its interpretation more difficult. In consideration of the above, therefore, the work addresses these aspects by developing a more efficient and effective safety management system and risk assessment modelling for offshore platform design process in subsequent sections.

2.5 Implementation of Safety in Design

Both the feasibility and conceptual design studies are conducted at the initial design stage of an engineering product. The purpose of the study in the feasibility design stage is to evaluate whether or not further development of an engineering product is technically feasible and commercially viable. The safety evaluation at the feasibility design stage usually plays a relatively subordinate role in determining whether to develop a product or not. Therefore, the risk estimation at this stage will be targeted at comparing different factors with respect to safety. The resultant outputs at this stage are expressed in the form of ranking of the alternatives rather than estimation of definite risk levels. As a result of this, in the feasibility phase, risk analysis is carried out to compare and/or rank alternative solutions. In addition, it will also be used to identify areas of uncertainty where detailed studies may need to be conducted later. The objective of risk analysis in the conceptual design stage of an engineering product is to provide safety-related input in the process of developing and selection of an acceptable product. The conceptual design must satisfy the operator and/or customer, as well as company's safety and economic concerns in order to demonstrate compliance with the governing regulations (An & Wright, 2001).

It is important to note that, due to high level of uncertainties that may be associated with the information and factors used in the decision making process, there may be the need to apply common sense and ensure that all issues are identified and effectively addressed. At the initial design stages, incomplete data and high level of uncertainty may not allow traditional methods to be effectively and efficiently applied to model cost and, safety for making design decisions and/or selecting the most desirable options. Thus necessitate the need at this stage to apply such techniques as approximate reasoning approach which may be more appropriate. This approximate reasoning approach usually involves the use of fuzzy sets and can be referred to as fuzzy reasoning approach (FRA). Some modifications have been incorporated with approximate reasoning for more effective and efficient safety modeling and decision making (An & Wright, 2001).

The fuzzy reasoning approach can be employed to produce design rules which can be used to build up a design support system. This safety-based design support system incorporating the approximate reasoning approach may have the following advantages (An & Wright, 2001);

- It allows the analyst to evaluate the risk associated with item failure mode directly using the linguistic terms with confidence.
- It enables the processing ambiguous, qualitative, or imprecise information, as well as quantitative data in an integrated manner.

The design process proceeds further after the selection of the best design option. The more the information becomes available the more detailed the safety analysis will be possible. Safety analysis and decision making may need to be carried out at the next level. At this stage, it may be the case that only part of the information is complete for safety modeling while the remainder is still incomplete. This creates problems involving the study of both complete and incomplete data for safety based decision making. This may necessitate the need to develop new technique to model both complete and incomplete data.

As the design proceeds further, for example, to the detail design stage, it first get to a stage where sufficient information is generated for carrying out design optimisation based on safety assessment. At this stage, safety may be assessed using various safety assessment techniques in terms of likelihood of occurrence and magnitude of consequences. A mathematical model consisting of safety, cost and reliability objectives can be developed and then formal decision making techniques can be used to process the model in order to optimise the design (Bazovesky, 1961).

2.6 Review on the development of Risk Assessment Methods

The concepts of safety and reliability were first introduced in aeronautical industry following the development of air transportation in the 1930s. Within this period the aircraft engineers were made conduct careful studies of the statistical data on failure rates of aircraft components with the aim of achieving improvement in their design and accidents prevention. This effort soon open the way for a number of courses and books on safety and reliability analysis, as well as related statistical techniques (Bazovesky, 1961).

The above development resulted in increasing the popularity level of the probabilistic safety and reliability analysis methods and eventual emergence of safety and reliability as a branch of engineering in the US where safety issues were accorded high priority in the 1950s, particularly in the aeronautical and nuclear industries. Also in focus within the period were the needs to study the impact of human error on these systems and how to prevent them. The first-ever analysis of component failures and their effects on system performance and on the safety of humans and property was performed (An & Wright, 2001).

During the same period another milestone achievement by Watson led to the development of the fault tree concept for assessing the reliability of a system designed to control the Minuteman missile launch (An & Wright, 2001). As mentioned earlier this concept was further refined by Boeing Co leading to its extensive application till date. In efforts to further complement this technique, failure mode, effects and criticality analysis (FMECA) was also developed in the early 1960s (Wang & Ruxton, 1998).

Further efforts were also intensified following a series of missile accidents and the growing public concerns regarding safety. Accordingly, the U.S. Air Force conducted several safety studies in order to ensure the adoption of system safety analysis in the aeronautics and nuclear industries. As a result safety awareness soon attained essential status especially to the developers in hi-tech industries as such classification of potential accidents, in terms of frequencies of occurrence and consequences were considered in the design process on a 'right-first-time' basis. It also became clear that integrated studies were needed to detect and reduce potential hazards of large engineering products. Consequently, several standards regulating safety and reliability were developed and these efforts were similarly adopted in the UK (An & Wright, 2001).

In the mid 1960s, fuzzy sets theory was developed precisely in 1965 through the works of Lofti Zadeh who conceived many of its applications initially in the area of industrial controllers (Dubois & Prade, 1991; Bandermer & Gottwald, 1995; Klir & Yuan, 1996). From this period onwards fuzzy sets and fuzzy logic witnessed a steady growth, it soon became a useful tool for application in other fields such as engineering, operational research, mathematics and most prominently in computer science (Sinha & Gupta, 2000). Zadeh (1992) stated that one of the basic aims of fuzzy logic is to provide a computational framework for knowledge representation and inference in an environment of uncertainty and imprecision. Since then fuzzy logic application continue to receive wider applications in the area of risk assessment due to its ability to effectively process information with some level of uncertainties. Fuzzy sets application in risk assessments are found in various works such as (Kosmowoski & Kwesielewicz, 2000; Richei *et al,* 2001; Sii *et al* 2001; Wang, 2000,).

In the 1970s, several innovations were adopted in order to advance industrial safety prediction methods. For example, in the nuclear power industries, accident scenarios were considered. These scenarios covered system failures and operator error during tests, maintenance, operations and reactor control. Following this development several new methods were developed including Event Tree Analysis (ETA). In addition, from the aeronautic industry emerged a Fault Tree Analysis (FTA) method which soon gained popularity and was adopted by other hi-tech industries. The Probabilistic Risk Analysis (PRA) methods were also developed for the evaluation of the performance and system maintenance (An & Wright, 2001).

Following special interest in safety management in the US, the then President Carter appointed a commission to advise on safety management which came up with some strong recommendations including the need for the application of PRA methods in the design of large, expensive engineering products. The committee also recommended that reliability data and human error must be considered when assessing the safety of such projects. Since then the oil & gas, chemical, railway and auto industries have widely adopted reliability and safety assessment techniques. Accordingly, applications of these techniques were discovered to cut across a range of activities and systems with different technological structures. Probabilistic reliability, availability and safety criteria were increasingly used-sometimes as self-imposed design goals.

Overall, safety criteria began to play a key role in the product design process (Cross, 1994; Villemeur, 1992).

In the 1980s, reliability, availability, maintainability and safety assessment techniques became widely adopted during the period, in efforts to control and manage major industrial hazards. This produced a distinct engineering discipline safety like others used in engineering design and involves concepts, measurable quantities and mathematical tools as well as methods for measuring and predicting these quantities (Villemeur, 1992). As designers began to rely more heavily on computers, greater numbers of analysis techniques (i.e. ETA and FTA) were incorporated into different codes of practice. Expert systems were also widely applied in combination with computerised assessment tools (An & Wright, 2001).

Following the growing technical complexities of large engineering products and the public concern regarding their safety resulted in generating great interest in the development and application of safety assessment procedures. It is evident that the above mentioned development, encouraged application of safety and reliability analysis in engineering product design in modern industry.

Also in the 1980's, Bayesian network was introduced, this method also deals with the mathematical modelling of expert opinions. Bayesian models have been applied in safety analysis for the assessment of rare events, such as catastrophic occurrence in complex technical systems (Coolen, 1996; Guerin *et al*, 2003; Aven & Porn, 1998). This technique is used to process experts' data to conduct a quantitative risk analysis (QRA) of rare events despite difficulties or lack of adequate failure information needed to compute relative frequencies.

In 1990's, the safety analysis advancements resulted in the inclusion of many more factors such as socio-technical and further studies towards the development of new mathematical models. The challenges at this time include the need to deal with uncertainties associated with the risk information which mathematical modelling can handle with great efficiency. Most of the mathematical based models developed within the period comprised of both the probabilistic and non-probabilistic (Garrick & Christie, 2002).

Some of the traditional risk assessment methods mentioned in this section will be further discussed in the following section.

2.7 A Review of some Traditional Risk Assessment Methods

However, for the purpose of having better understanding, and given the relevance of the topic, some traditional risk assessment methods are reviewed and summarised.

2.7.1 Preliminary Hazard Analysis (PHA)

The method was originally used by the US Army in the early 1960's, for the safety analysis of missiles and this use has since been extended to other fields. Following identification of hazards, its potential causes and consequences then possible preventive or corrective actions are listed. This method can be described as inductive and qualitative technique, and is formatted in a tabulated form (Ericson, 2005).

Advantages: - Simple to use, fairly broad in scope and allows identification of hazards at an early stage. It can help the team of analysts to develop operating guidelines for application throughout the system's life cycle.

Drawbacks: - Preliminary studies need to be complemented by other studies to achieve the desired result. It is usually a precursor of other hazard analysis studies.

Related development: - PHA was further developed to include the rough estimates of the occurrence probability which is referred to as Preliminary Hazard & Risk Analysis (PHRA).

2.7.2 Failure Modes and Effects Analysis (FMEA)

FMEA was first used in 1960's in the aeronautical field for the analysis of aircraft safety. Its use was initially restricted to aeronautics, aerospace, and nuclear engineering. The uses were later extended to the chemical industry and other industrial sectors (Ericson, 2005).

The procedures applied in this method include assessment of effects of each potential failure mode of the components of a system on the various functions of the system, and identification of potential failure modes impacting on the availability, reliability, maintainability, and safety of the system. Its approach is inductive or qualitative and is formatted in tabulated form and accompanied with recommendations (Ericson, 2005).

Advantages: - FMEA is a very specific and useful tool for assessing hardware failures to ensure that all conceivable failure modes have been identified right from the design stage. It encourages planning of maintenance procedures corresponding to each failure mode. It has the ability to integrate reliability and safety requirement holistically.

Drawbacks: - The method is time consuming and difficult to apply in a very complex system. Generally it identifies only single failure event and must therefore, be complemented by the study of failure combinations resulting in undesirable events. The approach does not cover human and organisational aspects of failure effectively.

Related development: - FMEA was further extended to develop Failure Modes and Effects Criticality Analysis (FMECA), which considers the probability of each potential failure mode and the criticality level of its effects or consequences. Criticality is determined by the "probability-severity" pair, even though FMECA allows for qualitative ranking. In recent work in 2002, efforts were made to integrate fuzzy logic with FMEA analysis for reducing variability and/or uncertainty of different expert's opinions in the assessment process (Xu *et al,* 2002).

2.7.3 Fault Tree Analysis (FTA)

This method was developed in the early 1960's by the Bell laboratories and refined by the Boeing Company for safety risk assessments (predictive and quantitative analysis). However, the technique has also been frequently used for accident analysis, as it identifies the interrelationships between causes and their logic. It is a typical tool for system engineering, designed for safety and reliability applications. It is only a method not a theory about causes of accident which has increasingly been used in several industrial sectors since 1965, particularly the high-tech industry such as nuclear, chemical process and, offshore oil and gas (Suresh *et al* 1996; Vario, 2002).

The FTA lists all components of a system that are represented in a logical diagram showing the way their failures interact and result in an unwanted or undesirable event (top event). This technique uses deductive approach starting with top event like accident or incident. The main aim at this stage is to identify causes or initiating events and their logic combinations using "AND"/"OR" symbols of Boolean algebra (Wang & Ruxton, 1997).

The FTA is a deductive method used for qualitative analysis of causes and also quantitative probabilistic assessment (QRA). Its format is a logic diagram of a "top-down" tree structure (Ericson, 2005).

Advantages; The fault tree may help to order the complex information about an accident that has happened. The method is most suitable for technical (engineering) systems, although it allows the inclusion of human errors or organisational factors as basic or initiating events. Its uses can be classified as simple or complex depending on the system being analysed. However, this is considered as one of the best-known methods employed in safety analysis, particularly for QRA.

Drawbacks; The method can be costly and more time consuming, even when conducted with the aid of computer. A fault tree is not a model for all likely to occur in a system, it is rather a model of the interaction logic between events leading to the top event. The construction of the tree depends on the analyst's skills and ability to conduct the reliable analysis, as the analyst can miss some causes (Suresh *et al,* 1996). These weaknesses form major impediment against the application of this method in the current studies.

2.7.4 Event Tree Analysis (ETA)

This method is also referred to as "consequence tree"; it was first applied in 1972 to assess risks associated with nuclear power plant in the USA (Villemeur, 1992). It has since then, been widely applied particularly in the framework of probabilistic risk assessment in nuclear power plants.

The basic principle applied in this method is to allow the study of potential "accident sequence" and the quantitative (probabilistic) assessment of each possible sequence; it works in the opposite way to FTA. The analysis starts by considering an "initiating event" and then with other events relative to the elementary systems, to construct the so-called consequence trees (Ericson, 2005).

The approach is generally inductive and used for quantitative analysis of consequences and also quantitative (probabilistic) risk assessment.

Advantages: - Its uses can be simple or complex depending on the system under analysis. It helps in the identification of control measures for reducing the harmful consequences of critical initiating events. Well suited for analysing events which can have several different outcomes.

Drawbacks: - The method does not describe the causes of the "intermediate events" in a clear manner. It can easily grow very large, and the analyst may never be sure whether all potential accident sequences have been identified. The construction of the tree depends on the analyst's skills and ability to conduct the analysis, as the analyst will require training (Villemeur, 1992). These weaknesses create major limitations for the application of this method in the current studies.

2.7.5 Hazard Operability Studies (HAZOP)

This approach was developed in ICI Petrochemical Division in 1963 in the UK. The first published paper on HAZOP was from Herbert G. Lawley, in 1974 (IChemE, 2002). This approach is generally considered to be "process industry" oriented mostly used in the chemical, pharmaceutical and food industry. It uses simple guided words such as No/Not/None, More, Less, Reverse etc to enable analyst find the deviation from the normality. It is also inductive and qualitative, and is presented in tabulated form.

Advantages: - It is a very useful method in identifying high hazards requiring further analysis and/or quantification, especially in the process industry. It can detect weaknesses early in the design stage.

Drawbacks: -It is expensive and would require a large team of analysts to explore as well as time consuming. It is a complicated process of analysis and therefore may result in some hazards to be missed.

Though this method is widely used in the oil and gas industry but the combination of the weaknesses mentioned above and its reliance on expert assessment based on historical data without due regard for improvement in safety is considered to have a conservative approach towards consequence. Thus the need for the introduction of method based on fuzzy logic approach which has the ability to deal with combination of information.

2.7.6 Fuzzy Logic Approach

Fuzzy logic can be described as a type of mathematical logic in which truth value is assumed to belong to a continuum of values range between 0 and 1. Fuzzy logic can also be considered as a form of multi-valued logic derived from fuzzy_set theory applied to deal with reasoning referred to as fuzzy reasoning approach that is approximate rather than precise. Fuzzy reasoning approach has the ability to operate like human mind by effectively employing modes of reasoning that are approximate rather than exact. This enables the specification of mapping rules in linguistic rather than numeric terms, and approximate reasoning rather than precise. In other words, fuzzy reasoning approach relies on fuzzy sets to define fuzzy operators and can be applied in situation where the appropriate fuzzy operator is uncertain thus necessitating the use of *if–then* rule, or constructions that are equivalent, such as fuzzy associative matrices. These rules are constructed to express or transform human knowledge to knowledge based or rule-based (An *et al*, 2007). One of the most important attributes of fuzzy reasoning theory is the provision of a systematic procedure for transforming human knowledge into a non-liner mapping. A fuzzy *if–then* rule is usually expressed in form of some words which are characterised by continuous membership functions (MFs) for example "*if* variable *is* property *then* action".

However, like any other method fuzzy logic reasoning approach has its advantages and disadvantages as listed in the following sections.

Advantages of fuzzy reasoning

- It has the ability to integrate expert knowledge, engineering judgement, historical data and other risk analysis information to handle the safety and risk assessment in a more consistent manner;
- It can make use of ambiguous, imprecise, incomplete and uncertainty information in the assessment;
- The risk can simply be evaluated using the linguistic expressions which are employed in conducting risk assessment;
- It offers a more flexible structure for combining failure occurrence and consequence.

Disadvantages of fuzzy reasoning

- Possible human error arising from actions of risk analysts will affect the results
- Possible subjectivity in deciding boundaries by the expert's.
- Possible uncertainties and the dispersions during de-fuzzification

This method draws it major strength in its ability to reduce level of uncertainty in the data to a certain degree however, further improvements may be required to ensure more acceptable results. Such improvement in this work include introduction of an additional parameter on consequence probability to factor-in improvement in safety to ensure achievement of more refined results to encourage decision making. In addition to the above innovation, the author will integrate fuzzy reasoning approach with the concept of design for safety to further ensure more acceptable results are achieved.

The concepts of safety and the evolution of safety thinking over the past decades are reviewed in the previous sections leading to the specifics of the concept of “design for safety” which will be the main focus of discussion in the subsequent sections.

2.8 Design for Safety

"Design for safety" is a process of identifying hazards, estimating the associated risks before finally classifying them in two basic parameters of occurrence probability of each hazard and the magnitude of their possible consequences to enable design review and mitigation (An & Wright, 2001). For example, in the UK, the concept of "design for safety" was first introduced in aerospace, nuclear, chemical process, marine, offshore, railway and other industries for many years. It is important to note the focus at this stage is the selection of the most effective design option within reasonable time to avoid the effect of late decisions which often jeopardise the balance of the whole project.

"Design for safety" supports the decisions making at the early design as a way of achieving a more significant impact on the performance of an engineering product compared to the decisions made at later stages in its lifecyc1e. In the UK for example, industries are made to comply with several safety case regulations which became effective in recent years such as Offshore Installations (Safety Case) Regulations and Railways (Safety Case) Regulations.

An & Wright, (2001) stated that when an engineering product is designed, the design for safety process is applied to identify all possible failure conditions, assess how frequently they may occur and determine how serious their consequences may be. For example, for an infrastructure or a railway vehicle or more specifically an offshore platform, the following risk factors need to be taken into account in design process. These include blowout, fire, explosion, falling objects, ship and helicopter collisions, earthquakes, extreme weather conditions, loss of stability, and/or relevant combinations of these accidents etc.

Design for safety, via the full quantification of hazard consequences and probabilities, can provide statistics that describe risks. When risks (qualified or quantified) are judged to be unacceptable with respect to corresponding criteria, the design may need to be modified. Cost benefit analysis may also be applied to produce a design with optimal safety. Therefore, a design for safety framework is expected to be developed to allow various safety assessment tools to be applied individually and/or in combination so that as the design process advances and the available information increases in detail, safety assessment can move from an assessment function to a decision making function and finally to a verification function, ensuring that the final design meets defined levels of safety (Ruxton & Wang, 1992). Design for safety constitutes five phases namely problem definition, risk identification, risk estimation, risk evaluation and design review.

It is obvious that, “design for safety” may be required when designing an engineering system such as offshore platform in order to identify all possible failure conditions, assess the frequency of their occurrence and analyse their possible consequences as well as determine or estimate the level of impact. This can be achieved through the application of various safety analysis techniques in the design process.

Usually, expert opinion or judgement is used to assess the probability of occurrence of a system failure event. This is a matter of judgement, normally based on the experience gained through operating similar system. However, due to sometime subjective nature of this type of judgement, fuzzy reasoning approach (FRA) and/or other quantitative techniques may be deployed to effectively deal with the associated uncertainties (An, 2003a).

Consequence analysis varies with the value attached to human life or loss of any nature. The magnitude of failure consequence has over the years been produced using a combination of experience and computational methods. However, the need to explore more analysis techniques will continue as a way of responding to the emerging technological advancements.

Quantification of consequences and probabilities of hazards through the process of “design for safety” will provide figures which best describe the risk level. These figures are used to determine whether the risk level is acceptable or not. The level of risk determined either through qualification or quantification techniques when estimated to be unacceptable relative to the corresponding criteria, the design procedure may have to be modified. This modification can be achieved by the provision of a set of protection system such as alarm or other complimentary element or even use of more reliable components, needed to reduce risks through design process (Wang & Ruxton, 1998).

Risk reduction can be achieved by lowering the frequencies of unacceptable system failure events and/or magnitude of their consequences to an acceptable level. Analysis of cost of providing safety may also be conducted with a view to determining whether or not the cost is within budget.

The constraints associated with the "design for safety" process need to be highlighted in order to achieve the desired integration. The constraints or difficulties associated with "design for safety" include the problems of getting sufficient data, effect of multiple factors or processes, complicated decision-making process etc (An, 2003a; Wang & Ruxton, 1997). Details will be discussed in Chapter 4.

2.8.1 "Design for Safety" in Offshore Industry

In the offshore sector, some of the major accidents generated a lot of interests leading to more intensive efforts in the area of development of more effective safety and reliability management methods. The public inquiries arising from the North Sea accidents at Ekofisk Bravo, Alexander Kielland, West Vanguard, and Piper Alpha became the rallying points focused on safety and reliability issues, thus necessitating tremendous efforts in areas of research projects to improve the safety and reliability of offshore systems.

Following the publication of public inquiry report on Piper Alpha in 1990 (Cullen, 1990) in the UK, the responsibilities for offshore safety regulations were transferred from the Department of Energy to the Health & Safety Commission (HSC) acting through the Health & Safety Executive (HSE) as the single regulatory body for offshore safety. Thereafter several new regulations were also issued by the UK HSE such as Safety Case Regulations 1992, PFEER 1995, MAR 1995 and DCR 1996 (HSE, 1992). The main feature of the new offshore safety regulations in the UK is the absence of a prescriptive regime and defining specific duties of the operator and definition of what “adequate means” in reference to safety. The regulations set forth a high level of safety objectives while leaving the selection of particular arrangements to deal with hazards in the hands of the operator. This is in recognition of the peculiarities of hazards related to offshore product based on specific functions and site conditions. The new safety case regulations require operational safety cases to be prepared for all offshore installations. Additionally all new installations require a design safety case.

In a related development, UKOOA with the assistance from the UK HSE produced "The industrial guidelines on a framework for risk related decision support" for UK offshore oil and gas industry (UKOOA, 1999). An & Wright, (2001) mentioned that these guidelines provide way for assessing the relative importance of various codes and standards, good practice, engineering judgement, risk analysis, cost benefit analysis, company values and societal values when making decisions to develop an offshore project.

In general, the framework could be usefully applied into wide range of situations. The aim at this stage is to support major decisions made during the design, operation and decommissioning of offshore installations based on safety assessments. This in particular provides a sound basis for evaluating various options that need to be considered at the feasibility and concept selection stages of a project, especially with respect to "major accidental hazards" such as fire, explosion, impact and loss of stability.

2.9 Safety Case

The regulation requires that a safety case should be accompanied with sufficient particulars to demonstrate that hazards with potential to cause major accidents have been identified, risks properly evaluated and measures have been taken to reduce them to As Low As Reasonably Practicable (ALARP). In addition it should also demonstrate that safety analysis and cost-benefit analysis methods have been deployed in order to adequately control safety. This further demonstrates that the safety case requirements fall within the concept of design for safety.

This new concept of Offshore Installations (Safety Case) Regulations allows operators and/or duty holders to have more flexibility in tackling the offshore safety problems. Offshore duty holders may use various safety assessment approaches and safety-based decision-making tools to examine all safety-critical elements of offshore installations, wells, infrastructures, operations management and maintenance to optimise safety. This may encourage offshore analysts to develop and employ novel safety assessment and decision-making approaches to deal with offshore safety challenges.

2.10 Summary

In this Chapter the concept of design for safety is described, its attributes and processes also enumerated. This concept has its support from the various accidents and incident reports notable among them is the Lord Cullen (1990) which recommended its adoption for offshore facilities development. The Chapter also enumerated difficulties negating the application of design for safety.

One of the most notable issues raised in this Chapter is the need to integrate the principles of fuzzy reasoning approach within the concept of design for safety in order to have holistic approach to deal with the uncertainties in the risk information for the assessment of offshore platform associated risks.

This Chapter further reviewed the concepts of safety and the evolution of safety thinking over the past decades. This review revealed that at the beginning, safety literature and practice concentrated on technological failures and operator errors. In the late 1970's and 1980's, safety management began to focus on other areas than just engineering system to more comprehensive complex concepts. This development recognised the need for the involvement of top management in order to achieve any meaningful success. This modest progress facilitates the development of modern safety theories.

HSE (UK), standard safety management system model has been presented and discussed, and the philosophy and principles of Health & Safety (H&S) provision have also been explored.

Also discussed in this Chapter are some historical perspectives of safety analysis approaches which have been outlined ranging from earlier tools for identifying hazards and technical risks, to modern tools for assessing failures. Some of the most popular methods used for identifying hazards and assessing risks associated with technical systems have also been reviewed. The review shows that each method has its own advantages and limitations suggesting the desirability of using some combination in certain situations in order to achieve the desired result. Most of these theories and methods were initially developed to deal with high-tech industry risk but only a few can be applied effectively in complex design processes with high level of uncertainty such as the offshore installations.

PHA would be used at the preliminary stages to generate lists of hazards and provide basis for achieving rough estimation of failure occurrence probability. This effort will provide input required for further analyses using FTA and FMEA combined to determine the various interactions leading to top event, their effects, and criticality levels to guarantee successful integration with other compatible methods.

The chapter also discussed, “design for safety” methodology with the overall objective aimed at achieving safety improvement through the design of offshore platform using appropriate technology and available finances.

The process would be deployed to generate information regarding identification of failure events to be applied through modelling procedure with a view to achieving proper integration with other methods possibly to deal with uncertainties such as fuzzy reasoning approach based method. In this study the author highlighted intention to introduce a third input parameter referred to target consequence probability to the existing two parameters to further reduce the weaknesses of the fuzzy reasoning approach and reinforce its strength to achieve a more refined result.

Furthermore, the author applied weight factor to deal with expert judgements where there exist uncertainty in the risk date and to avoid the dispersions.

In conclusion detailed process of design for safety is further enumerated in subsequent Chapters to demonstrate how the integration will be achieved in order to develop a risk assessment model for offshore platform design with the ability to effectively deal with associated uncertainties in risk information.

CHAPTER 3

Methodology

3.1 Introduction

This Chapter gives detailed highlights on the methodology for this study as enumerated in Figure 3.1 which shows the various steps adopted for the conducting this research work.

Chapters 1 & 2 discussed the basis for further work on safety of offshore platforms through the literature review. This Chapter presents how the research is conducted in details. These details have been structured from the definition of research aim and objectives to data collection and analyses leading up to the development of a proposed risk assessment model. This model will then go through testing procedure before application in a case study using data collected from the industry in order to validate its efficiency based on the results obtained.

3.2 Research Methodology

An offshore platform design for safety model to be developed will enable the application of the existing safety assessment techniques, intended to encourage smooth progression from a qualitative method to a quantitative method, and from an assessment function to decision making function, before ultimately moving to verification function (Ruxton, 1992).

As stated earlier the research methodology framework as shown in Figure 3.1 is used to elaborate step by step details of processes of this research project, which is described in the subsequent sections.

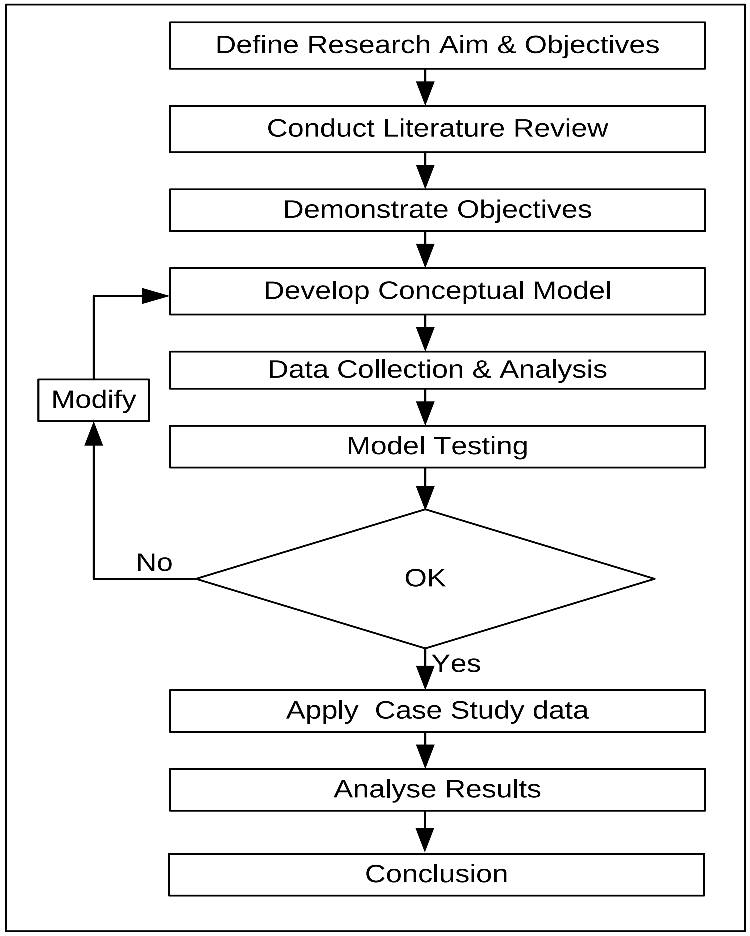

Fig. 3.1 Research Methodology Framework

3.3 Research Aim and Objectives

3.3.1 Research Aim

The aim of this research is to develop a "design for safety" based assessment technique for the design of offshore platforms in order to facilitate decision making.

3.3.2 Research Objectives

The objectives of this research are outlined to ensure the achievement of the above stated aim through the various steps summarised as follows:

1. To examine the risks, their possible causes and impacts on offshore platforms through design process.

2. To study some of the traditional safety assessment methods with a view to identifying areas that still need to be addressed.

3. To develop a new safety assessment model to effectively deal with the gaps identified in objective 2.

4. To verify the performance of the proposed safety assessment model in a case study using real industry data.

5. To recommend safety improvements for the industry and suggest future works based on performance of the model and results obtained

The above highlighted steps are further discussed in section 3.5 which elaborates on how each of the five objectives is met in relation to the overall thesis structure.

3.4 Literature Review

This is a continuous process through most part of this work as a means of ensuring no information is left out. This review is conducted to help establish basis for the research especially in identifying the areas where gap exist as well as in making informed decision about the most suitable modelling processes to be developed for processing data in order to facilitate the achievement of the objectives.

As stated in Chapter 1, the complex nature of offshore platform is associated with high level risk arising from continuous expansion and increased level of innovations as may be necessitated by the dynamic nature of the industry.

Several literatures have been written about the safety need in this area but yet risk mitigation efforts are met with increasing challenges. Lois *et al*, in his work of 2004 stated that the magnitude of the offshore safety problems requires continuous efforts with a view to eliminating or reducing hazards. The task of safety analysis in this context will mainly concentrate on the prevention and/or mitigation or control of risks through the entire life of the project.

According to Raftery, (1993), the consensus of opinion among the experts on risk is unanimous in accepting the inadequacy of software only solutions to the risk management problem as currently being pursued.

Wang *et al*, (1995) described the risk associated with marine systems as a measure of exposure to the possibility of economic or financial loss or gain, physical damage or injury or delay as a consequence of the uncertainty associated with the pursuance of a particular course of action.

In considering this topic, a combination of several factors such as the importance of the subject of safety management for an offshore platform and its overall importance in the oil and gas industry, as well as the applicability of the proposed research works to enhance safety in the field provided the basis for the topic: "*Design for Safety framework ~~o~~for Offshore Oil and Gas Platforms"*.

Based on the review conducted so far, it is evident that most efforts made previously are still grappling with the issue of uncertainties associated with data on most marine systems such as offshore platform. In this study therefore, risk assessment model to be proposed will specifically target areas that will effectively deal with such uncertainties to enable informed decision-making based on cost-benefit evaluation.

3.5 Objectives

As earlier introduced in section 3.3 this section will further elaborate how each of these objectives is achieved in the current work.

3.5.1 Objective 1

Literature review on the development of a typical offshore project in general and offshore platform in particular. This works are discussed in Chapters 1 & 2.

3.5.2 Objective 2

Chapter 2 reviews the traditional safety analysis methods which are discussed band their merits and demerits highlighted. Accordingly, what is observed to be common with them all is their inability to effectively deal with uncertainties associated with risk data especially in systems of complex configuration like an offshore platform.

3.5.3 Objective 3

The foundation for the development of a new offshore platform safety assessment model is established in Chapters 4, 5 & 6 briefly discussed as follows;

Chapter 4 presents safe design approach and Chapter 5, deals with offshore platform safety framework, its development as well as introduction of a modified design for safety methodology for offshore platforms. This modification is intended for the achievement of proper integration with fuzzy reasoning approach (FRA) which is considered very reliable in dealing with uncertainties. Details of this are discussed in Chapter 6.

Chapter 6 is used to explain the concluding steps leading to the development of a knowledge-based risk assessment model (KBRAM). KBRAM is a composite model developed through the integration of concept of design for safety with the principles of fuzzy reasoning approach in order to improve the treatment of data uncertainties as this undoubtedly is a major gap that still exists in risk assessment efforts for offshore platform.

3.5.4 Objective 4

Chapter 7 demonstrates how the real data is used to verify the performance of KBRAM. This has been achieved through comparative analysis of the results from two fuzzy reasoning approach (FRA)-based models (Traditional two-input parameter TPRAM and the proposed three-input parameters KBRAM) using the same industry data and procedure.

The results obtained through the process above are used to reach some conclusions leading to recommendations and suggestions for further works as detailed in Chapter 8.

3.5.5 Objective 5

As mentioned in the previous section above, in Chapter 8, the results are used to recommend safety improvement in offshore platform design process and suggest areas for future works in order to facilitate decision-making.

3.6 Development of Conceptual Model

The information generated through the review of various methods of assessing risks for offshore projects will be used to establish solid basis for the development of suitable modelling technique to allow for the effective and efficient analysis of data. It is obvious that, analysis is very critical for the assessment of risk information related to offshore platform, especially its associated uncertainties which need to be adequately considered in the choice of processing techniques. Following the choice and development of the appropriate model there will then be the need for testing to ascertain its efficiency.

3.7 Data Collection and Analysis

3.7.1 Data collection

At this stage the real data collected from the industry will be used to test the performance of the proposed model. This data include failure frequency information and expert responses to the interviews and questionnaires which together constitute the necessary input for gathering information required for test running the model and its preliminary validation studies with regard to offshore platform risk assessment.

However, to accomplish this task the following requirements must first be satisfied, these are:

1. Search for existing records on the case studies via:

- Internet sources,
- Documents and publications, and
- Design management reports.

2. Conduct industry survey through

- Questionnaires, and
- Interviews.

3.7.2 Data analysis

Analysis of the data collected from industry has been conducted through the use of;

- Statistical or historical analysis,

- Other relevant programmes, such as, AutoCAD, Excel etc,
- Compare the results of the proposed model with the ones obtained using two parameters in order to validate the efficiency of the proposed model.

3.8 Model Testing

Testing of the developed model will make use of all the collected information to run through the procedures in order to generate results. These results will have two possible outcomes either satisfactory or not. If the outcome gives the desired result then the process will continue to the validation using real industry data or case study. However, if the outcome is not satisfactory then there may be the need for further verification of the adequacy of the data otherwise modification of the model may become necessary.

3.9 Summary

This chapter enumerated the tasks of accomplishing the process and procedures for the pursuance of the proposed studies dealing with the safety assessment for offshore oil and gas platforms. The Chapter also provided detailed discussion on the aim and objectives and how they have been interpreted in subsequent section of this work all through to the conclusion.

The validation of the model through case study is conducted to ensure that results generated have satisfied the main aim of the research which will be summarised in conclusion report to put forward recommendations for mitigation and further identification of areas for further works.

CHAPTER 4

Safe Design Approach for Offshore Platform

4.1 Introduction

Chapter 2 described a "design for safety" of an engineering system as a systematic approach used to identify and control high risks at the early design stages in order to reduce or eliminate major hazards. In this chapter, the concept of an offshore platform is highlighted and their design process is reviewed in efforts to lay foundation for the proposed design for safety framework. However, due to the complex nature of offshore platform and its safety assessment, coupled with lack of clear cut guidance for "design for safety" criteria all together make it difficult to fully integrate "design for safety" methodology in the active design process to an acceptable level. In this regard it is important to note that despite the continuous efforts in safety provision, major accident still do occur thereby necessitating further efforts such as the adoption of principles of "design for safety" in the design offshore platform as a way of complimenting existing methods for the achievement of improved safety.

Sequel to the above, a new "design for safety" based methodology is proposed in this work for offshore platform risk assessment. This proposed methodology comprises of various phases which are discussed with reference to their descriptions, objectives, and requirements.

4.2 Safe Design Method for Offshore Platforms

This section describes two major aspects of offshore platform safety requirement and engineering design methods which have substantial impact on design for safety in the offshore platform development projects.

4.2.1 Offshore Platform Safety

As stated in Chapter 1, an offshore platform is a complex engineering system composed of input from various engineering disciplines. This system requires special consideration in the area of safety through design. It therefore becomes imperative to think of integrating safety through the design process at early stages.

The identified inherent risks and the challenges posed to an offshore platform development project necessitate the need for continuous work in the areas of managing such risks. These risks have the potentials to cause injuries and/or loss of lives, degradation of the environment, and damage to the property or economic assets and will therefore require deployment of effective safety management approach (Khan & Amyotte, 2002).

The safety management approach in this context is needed for the establishment of appropriate risk elimination or reduction measures from the design to the final installation stages. This approach requires detailed hazard identification and risk assessment of possible failures in the design process (Vinnem & Hope, 1998).

The above could be achieved through the application of appropriate risk analysis techniques to enable integration of:

- risk assessment process into practice, and
- incorporation of safety procedures using design tools.

The offshore platform project faces critical safety challenges as described in Chapter 1, section 1.2. These critical risk challenges necessitate the need for continuous efforts to develop systematic approach aimed at controlling and monitoring safety from conceptual design phase to detailed design phase (Khan *et al*, 2002). An offshore platform as an engineering system has its design process based on the principles of engineering design methods as discussed in the following Section.

4.2.2 Engineering Design Methods

Engineering design can be described as a creative process beginning with the identification of requirements, definition of the system and the development of methods establishing the system in order to meet the desired requirements.

Engineering design can be divided into three main categories, which are as follows;

i. Original design: This encourages the production of an original solution for a system to perform a new function.

ii. Adaptive design: This suggests customising a familiar system to a changed function.

iii. Variant design: This involves changing the sizes and/or arrangement of certain aspects of the chosen system while the function and principle remain constant.

The above categories are applied in design of various engineering systems and they can be identified and analysed using their individual patterns to form series of steps required to organise and guide an engineering design. These steps can be referred to as an engineering design methodology (Cleveland & King, 1983; Cross, 1989).

The advantages of engineering design methodology include prompt and simple ways of generating and evaluating design solutions through a systematic framework for maximum efficiency and effectiveness.

Generally, there are two types of models available for most design processes of engineering project development such as an offshore platform, and these are descriptive and prescriptive types. The descriptive model describes how a design is done, while the prescriptive model gives detailed example of how the design engineer performs the process of design. When comparing the two models one cannot but conclude that, the descriptive type of model is subjective while the prescriptive is not. Both models offer rational systematic frameworks which simplify the design process and improve the performance of the design engineer.

The prescriptive model involves a more traditional approach consisting of steps from identification of needs through feasibility study, Preliminary study, detailed design, qualification testing, production planning, and acceptance testing for operations (Danish, 2006).

Both models have been carefully studied with regard to the offshore development (Khan & Amyotte, 2002). A combination of both heuristic and empirical knowledge is used in the design of offshore platforms. The design engineers used empirical knowledge to conceptualise an offshore platform as a complete system, while heuristics are used for general aspects such as layouts of an offshore platform.

For instance, heuristics are used in the design process of top side of an offshore platform, to locate the different compartments, activities, and items in three dimensional forms right from early stages of the preliminary design phases. However, as more detailed information is gathered, the design progresses to a more comprehensive preliminary definition of the design leading to completion of conceptual design phase from where detailed design commences (Paik & Thayambali, 2007).

The above clearly expressed reason why prescriptive methodology may not provide an absolute choice for the offshore platform development but may be used to explore all possible alternatives. In contrast however, descriptive methodology may be considered more appropriate in detailing the design requirements. Sequel to foregoing, a descriptive design methodology for the development of offshore development project is described in the following section.

4.3 Typical Phases for Offshore Project Development

The typical offshore project development phases are presented in a highly simplified sequential form as shown in Figure 4.1. However, in practice these phases will to a greater or lesser extent overlap, depending on the participants involved in the project, the choice of contract philosophy, contract types, etc. In this study however, these simplified phases have been expanded to produce Figure 4.2 adopting the principles of design for safety which will further be modified by integrating with the fuzzy reasoning approach in order to develop a new offshore platform risk assessment model details of which will be discussed in Section 4.4 (Wang & Ruxton, 1998).

4.4 Framework for Offshore Platform Development

Typically, a design for safety framework as described in the work of Wang & Ruxton (1998) shows the typical design process of complex marine and offshore products such as an oil and gas platform. This framework is found to be generally suitable for application in the design process for most complex engineering systems. However, project peculiarities may necessitate changes or even elimination of some steps, therefore, in this study a framework for the development of offshore platform is shown in Figure 4.2 and described in the subsequent sections as follows.

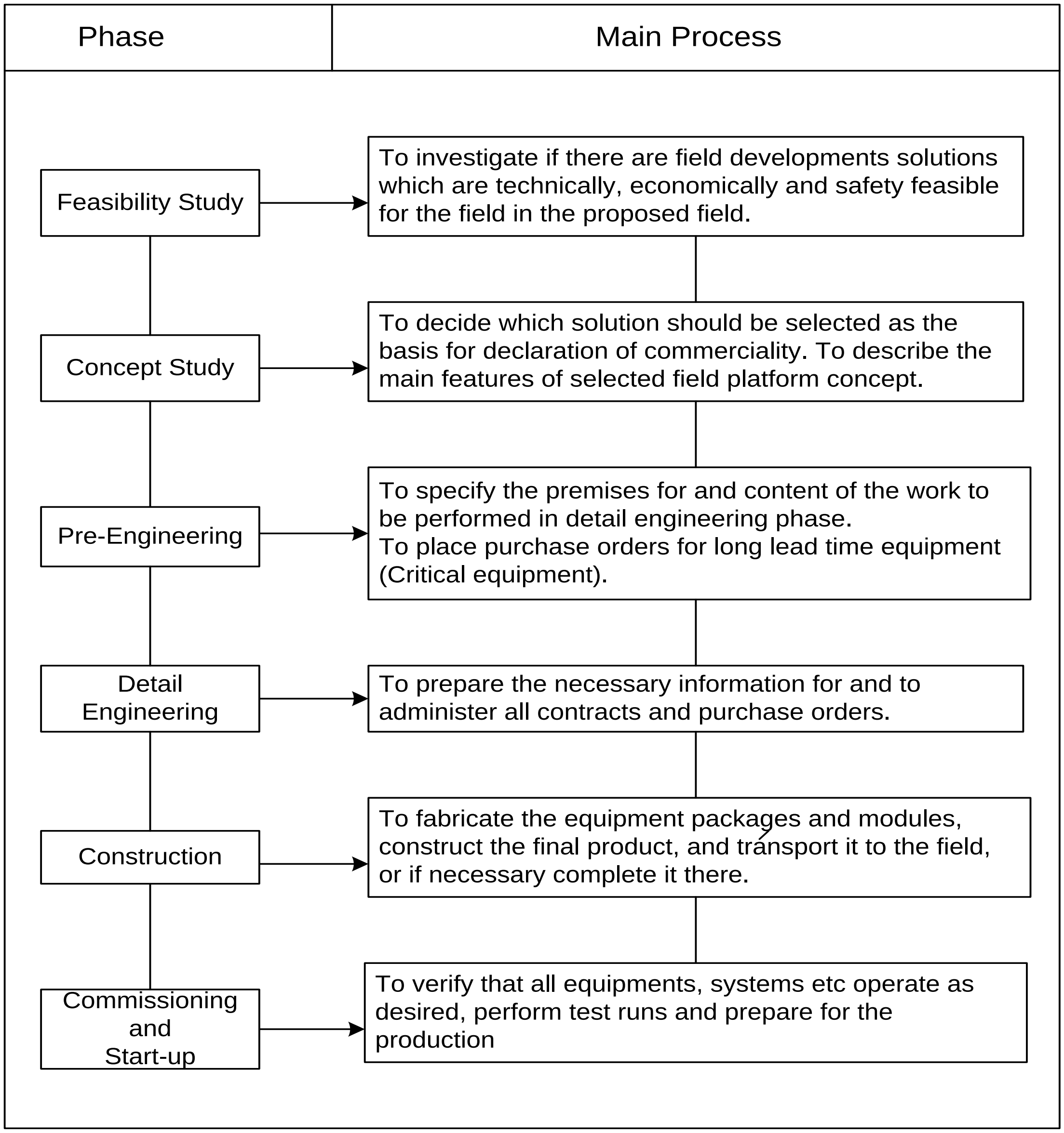

Fig. 4.1 Typical offshore project development phases

4.4.1 Planning/Feasibility Study

This phase of the design process is where information gathered regarding the project is further defined preparatory to commencement of work in the conceptual study phase. This process of refining the project objectives begins with the specification of needs, information gathering, conceptualisation, and definition.

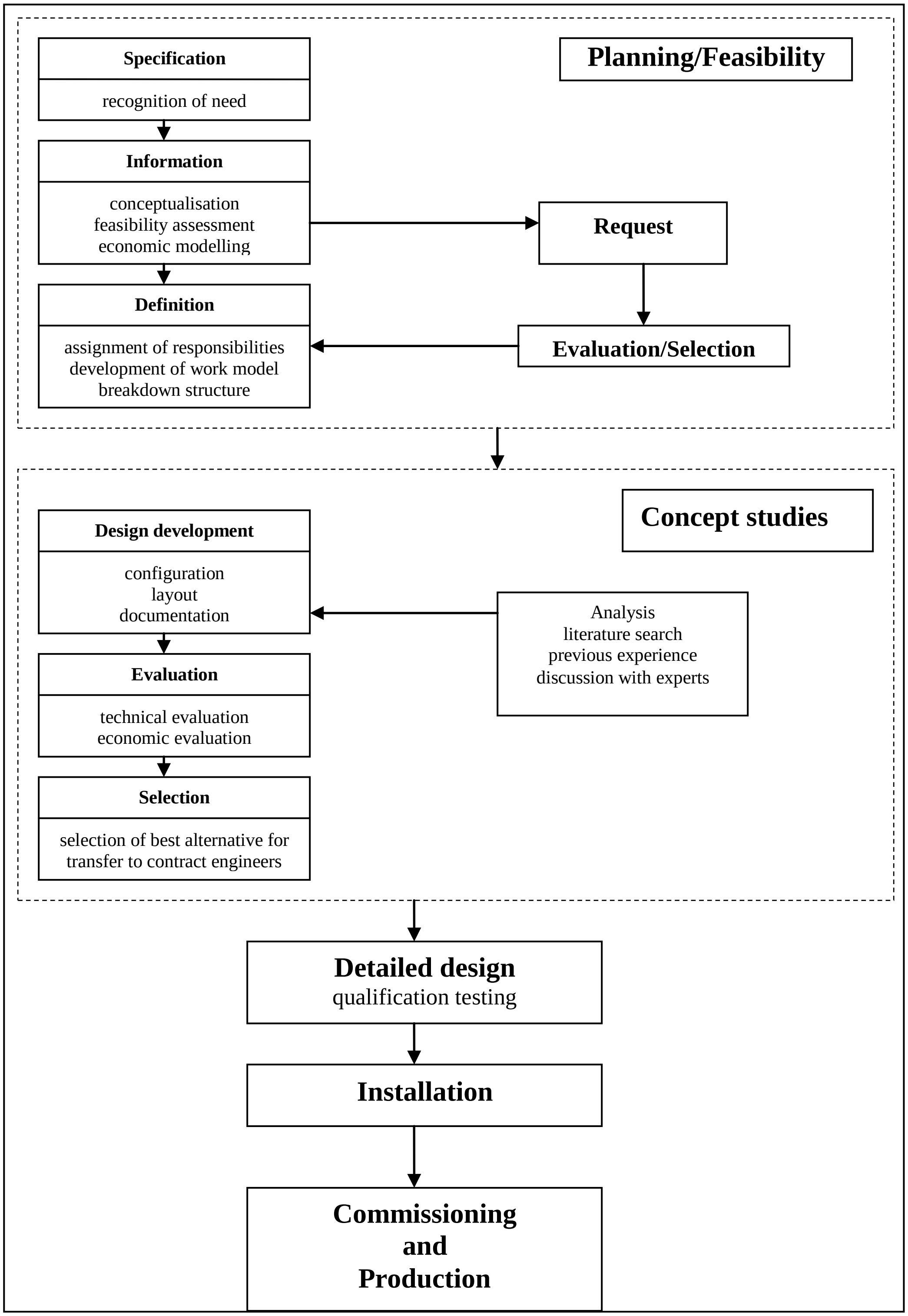

Fig. 4.2 Step by step design process for a typical offshore development

4.4.1.1 Feasibility assessments

The selection of the concept will then be subjected to some feasibility assessment to satisfy the project is both technically and economically realisable. The feasibility assessment is necessary in order to ensure that the selected concept is defined in such a manner as to guarantee continuity of the design. At this stage of the feasibility study of the project, the selected concepts viability would be defined in terms of meeting the desired objectives including safety standard requirements within the available resources, before carrying out further work on the project (Vinnem & Hope, 1986).

The establishment of the project requirements must follow the clear concept definition before the commencement of the preliminary design. This task is important and difficult part of the design process as these established requirements must be reviewed and revalidated continuously during the design process to ensure their conformity with the project goals and objectives.

4.4.1.2 Definition

This stage involves the studies of the various project elements within the approved concept in relation to the specified need for the establishment of requirements at every level. This procedure will be repeated continuously through the design process as the structure and its components are further defined, tested, evaluated, fabricated, and assembled into a functioning system. The next assignment requires the structure to be broken down into various work elements related to each task in the form of a family tree. This tree will provide basis for taking adequate inventories issues such as technical, schedule, and manpower (Wang & Ruxton, 1997).

4.4.2 Conceptual Design Phase

This phase of the design process is where information gathered from the feasibility study phase is further defined preparatory to commencement of work in the detailed design phase. This covers design development, evaluation, and selection of the prepared alternative for the design team to commence work.

4.4.2.1 Design Development

Following the definitions of the overall structures, layouts, and drawings of an offshore platform at the concept design phase, intensive analysis should be conducted at this stage. The analysis may include detailed literature search, analysis methods, previous experiences of similar designs and discussion with experts in particular fields. Testing may also be conducted at this stage if deemed to be cost effective (Pappas, 1994).

4.4.2.2 Evaluation

The continuous refining of the concept design layout, fabrication of the various elements will gradually be implemented. At this stage both technical and cost estimation would be defined in a more realistic manner. The technical evaluation is conducted in order to ensure that, the design specifics like stability, weight distribution, flow safety, and reliability are in conformity with the project requirements. The economic evaluation to be carried out must satisfy that aspects as cost of construction, equipment, operation and maintenance are all within the acceptable limit. Testing process at this stage may be necessary in order to ascertain that, the initial design stages have adequately been taken care of including both operation and maintenance procedures (Wang & Ruxton, 1997).

4.4.2.3 Selection

Further redefining of the design at this stage will be necessary if more than one alternative is involved in the evaluation of the process prior to the selection of the best alternatives.

The final step in the project design prioritisation and development process is project selection. The term selection relates to actual project implementation and therefore relates directly to the programming of funds in the safety improvement. Project selection is therefore an element of the safety improvement and financing programming process. Selection criteria may include:

• Funding availability and management commitment;

• Political and public support; and/or

• Existence of supportive planning, environmental and engineering studies.

4.4.3 Pre-Engineering (Detailed Design) Phase

At this stage all disciplines involved in the project are active in ensuring the design concept is translated into product parts. Evaluation of these parts is in line with the established specific design requirements produced in the conceptual design phase. The project costs continue to be authenticated at this stage and placement of purchase orders for long lead equipment as prior testing may be necessary for the validation of the design to confirm the installation meets the desired specifications.

4.4.4 Detailed Engineering, Production and Commissioning

Design review is conducted before the commencement of detailed engineering for the proper identification of the machines and tools required, and to determine the machinery operation to be used. Following that is the commencement of production before finalising the design process with commissioning, testing, and eventual start up of operation.

4.5 Modified Design for Safety Methodology for Offshore Platform

As stated in Chapter 2, the concept of design for safety methodology becomes more popular following Lord Cullen report of 1990, where the adoption of principles of design for safety from the early stages of the design process for an offshore system was recommended. The "Design for safety" as earlier referred to in Chapter 2 is a process of minimising injury or death of personnel, damages to offshore products and pollution of the environment (Lois, P. *et al*, 2002). It involves a methodology of incorporating safety into the design process from the early stages, which is achieved through a systematic approach to the identification and control of high-risk areas.

The constraints or difficulties associated with "design for safety" as discussed in Chapter 2 are considered in the process of model development based on concept of "design for safety".

The development of safety model through the design of such a structure like an offshore platform can be difficult which may require approximation, estimation and judgments by experts and operatives with adequate knowledge regarding the operation of the system (Wang & Ruxton, 1998). This effort may necessitate the need for the application of safety analysis methods either individually or in combination to conduct a qualitative or a quantitative safety analysis. However, the problem with application of these methods is the lack of specification of where and how to apply them or how they inter-relate. Therefore, these will certainly require good knowledge of qualitative and quantitative analysis techniques and how to apply them.

In view of the above, the design for safety framework developed for this study will aim to achieve integration of relevant safety assessment procedures where necessary, as the design progresses.

This modified design for safety methodology for offshore platform development comprises of mainly four phases as in general design for safety framework but expanded to meet the project requirements and the details, these phases are as follows (Umar *et al*, 2006);

1. Problem definition
2. Risk identification
3. Risk estimation
4. Design review

As referred to earlier design for safety is a progressive process where for example the information generated from the design review may be used to conduct the task of risk identification alongside the design goals defined in the problem definition phase. Figure 4.3 shows a typical design for safety framework.

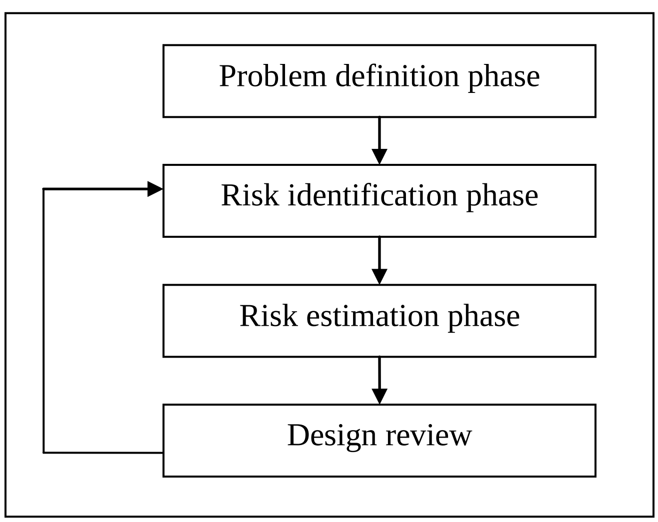

Fig. 4.3 Modified design for safety framework

Figure 4.3 shows a modified design for safety framework designed to ensure proper integration of with fuzzy reasoning approach purposely for the development of knowledge-based risk assessment model for offshore platform processes.

4.51 Problem Definition

The problem definition specifically involves the identification of the safety need conducted in relation to the project classification and the detailing product specification during the evaluation of the project design process. The specification of need is accomplished in the feasibility study process.

At this stage, the general safety need once established will lead to the production of more specific requirements for the actualisation of the project. The requirements for the operation and design relating to safety can be specified by using information generated through the definition of need, but this specification has to be broken down into component parts to enable proper assessment from the component level before progressing to sub-system and overall system levels.

At this stage the common factors that need to be considered may include.

- Sets of rules and regulations by the regulatory authorities and control standards,
- Deterministic life of the product, reliability, etc,
- Criteria referring to the probability of occurrence of various system failure events and possible consequence.

4.5.2 Risk Identification

Risk identification is the process of finding potential hazardous events, their respective causes and possible consequences. This progress achieved in the design process will advance from concept evaluation phase to preliminary design phase, the details generated at this stage will enable achievement of some reasonable level of progress in the risk identification process. The configuration of the system at all levels has been defined to allow the commencement of the process of risk identification. Risk identification is a very critical stage where a complete system safety check is conducted and proper measures are taken from early stages of design to prevent failures.

This phase requires experiences of the engineers and operators to be deployed at this stage in order to ensure identification of all possible failure events at each level. This would be achieved through the proper assessment of the effects of such facilities on the system safety and performance.

The various safety analysis methods may be incorporated into the risk identification phase in the design for safety framework either individually or in combination for a more effective identification process of risks associated with the system (Cross, 1989). However, the need to effectively deal with the problems of uncertainties associated with risk information as stated earlier in this thesis may necessitate the application of such methods as fuzzy reasoning approach (FRA) to conduct risk estimation (An *et al*, 2000b).

4.5.3 Risk Estimation

Risk estimation involves the use of identified failure or hazardous data to estimate possible consequence and overall risk level using combination qualitative and quantitative methods. Risk estimation process begins with the estimation of consequences of each failure event using qualitative methods if the identified event may not be readily quantifiable. However if the level of uncertainty is very high, subjective safety analysis methods such as fuzzy reasoning approach which has the ability to deal with uncertainty may prove to be more appropriate in executing this task (An *et al*, 2000b; Wang & Ruxton, 1998).

As the design progresses, more and more information regarding safety are generated to the level that minimal cut sets are identified. These minimal cut sets are elements leading to the system failure event (top event) and failure data of the basic events associated with them must have been collated, then quantitative risk estimation can be conducted. Cut set is a collection of component failure events, which are necessary and sufficient to cause the top event while minimum cut sets are a set of irreducible failure events leading to top event. The methods used in carrying out typical quantitative risk estimation may include fault tree analysis (FTA), event tree analysis (ETA), and simulation (Pillay & Wang, 2002 & 2003).

The probability of occurrence of each failure event associated with the minimal cut sets of a top event may be obtained either from historical analysis, and simulation, or from the data collection programmes and engineering judgement. The consequences of possible occurrence of a top event may be quantified in economic terms in relation to the loss of lives and/or property, and the degradation of the environment.

The information generated and result obtained from this phase may be used in the safety design review phases, and may also be useful in the development of operational and maintenance policies.

4.5.4 Design Review

Design review depends on recommendation arising from the result of risk estimation phase. It involves adoption of measures needed for effective reduction or elimination of risk through design process. This activity can be integrated into the evaluation and selection phases of the preliminary design process of an offshore system. Having determined the probability of occurrence of each serious system failure by the minimal cut sets associated with some basic failure events. Therefore, the task for effective reduction or elimination of unacceptable failure events, otherwise referred to as minimal cut set with the highest probability of occurrence, must be targeted for elimination. The process of eliminating such cut sets can be achieved by the deployment of safety measure which may include the provision of protection systems and alarm devices or recommending the use of more reliable components.

During the design review, risk mitigation measures must consider human errors and possibility of reducing its probabilities through the provision of sensing and alarm devices, and better training. Further efforts must be aimed at improving the inspection and maintenance policies to compliment others in reducing the probabilities of occurrence of system failure events (King, 1990).

Cost-benefit analysis should be made as a part in the design review process in order to facilitate decision making on the design. Cost-benefit analysis compares the cost of safety proposal and the benefit in real economic terms which provides basis for decision making on the design options.

This review action may use other formal decision making tools to process information generated from risk estimation phase. The design review makes use of these approaches to achieve optimal design alternatives and, the best maintenance and operational policies through careful studies of both design and maintenance procedures (Lees, 1980 & 1996).

4.6 Summary

This Chapter reviews design for safety concept for a complex engineering system such as an offshore platform. The review further highlighted offshore platform safety requirements with a view to integrating design for safety methodology preparatory to the development of a new knowledge-based model for the assessment of offshore platform associated risks.

Chapter 5 highlights the fundamental of fuzzy reasoning approach and demonstrate how the approach has been integrated with the principle of design for safety to develop the methodology for the risk assessment of offshore platforms.

CHAPTER 5

Fuzzy Reasoning- based Risk Assessment Approach

5.1 Introduction

In Chapter 2 various safety assessment approaches have been reviewed and offshore platform safety requirements have been highlighted in Chapter 4 with the aim of establishing basis for integration of concept of design for safety with fuzzy reasoning based risk assessment approach for assessing offshore platform associated risks.

In this Chapter however, detailed fundamentals of fuzzy reasoning approach are discussed to demonstrate how its principles have been integrated within the framework of design for safety thereby establishing foundation for the development of a knowledge-based modelling for the assessment of risks related with offshore platforms.

5.2 Fundamentals of Fuzzy Reasoning Approach

Fuzzy reasoning approach (FRA) is based on the principles of fuzzy logic which can be described as a type of mathematical logic in which truth value is assumed to belong to a continuum of values range between 0 and 1. Fuzzy logic can also be considered as a form of multi-valued logic derived from fuzzy set theory applied to deal with reasoning that is approximate rather than precise. As stated earlier fuzzy reasoning approach has the ability to operate just like human mind by effectively employing modes of reasoning that are approximate rather than exact. This enables the specification of mapping rules in linguistic rather than numeric terms, and approximate reasoning rather than precise. In other words, fuzzy reasoning approach relies on fuzzy Sets to define fuzzy operators and can be applied in situation where the appropriate fuzzy operator is uncertain thus necessitating the use of *if–then* rule, or constructions that are equivalent, such as fuzzy associative matrices. These rules are constructed to express or transform human knowledge to knowledge based or rule-based (An *et al*, 2007). One of the most important attributes of fuzzy reasoning theory is the provision of a systematic procedure for transforming human knowledge into a non-liner mapping. A fuzzy *if–then* rule is usually expressed in form of some words which are characterised by continuous membership functions (MFs) for example "*if* variable *is* property *then* action". Further descriptions of fuzzy reasoning approach are given in the following sections.

5.2.1 Background of fuzzy reasoning approach

A fuzzy set A on a universe of discourse U is defined as a set of ordered pairs (Bojadziev & Bojadziev, 1995)

$$A = \{(x, \mu_A(x)) \mid x \in U\} \tag{5-1}$$

where $\mu_A(x)$ is called the membership function (MF) of x in A that takes values in the interval [0, 1]. The element x is characterised by linguistic values e.g. in offshore risk assessment, the failure probability or likelihood (FP) is defined as very low, low, average, high and very high; the consequence severity (CS) is defined as negligible, marginal, moderate, severe, and catastrophic; and the risk level (RL) is defined as minor, tolerable, major, and intolerable. In fuzzy reasoning various types of MFs can be used, such as triangular, trapezoidal, generalised bell-shaped and Gaussian functions. However, the most frequently used in risk analysis practice are triangular and trapezoidal MFs. It is also important to note that, the most common fuzzy set operations are union and intersection, and that they essentially correspond to *OR* and *AND* operators, respectively for example consider two sets A and B to be two fuzzy sets (An *et al*, 2007; Bojadziev & Bojadziev, 1995; Maseguerra *et al*, 2003).

Union: - The union of A and B, denoted by $A \cup B$ or A OR B, contains all elements in either A or B, which is calculated by the maximum operation and its MF is defined as (Bojadziev & Bojadziev, 1995):

$$\mu_{A \cup B}(x) = \min\{\mu_A(x), \mu_B(x)\} \tag{5-2}$$

Intersection: - The intersection of A and B, denoted by $A \cap B$ or A AND B, contains all the elements that are simultaneously in A and B, which is obtained by the minimum operation and its MF is defined as (Bojadziev & Bojadziev, 1995);

$$\mu_{A \cap B}(x) = \max\{\mu_A(x), \mu_B(x)\} \tag{5-3}$$

As stated earlier FRA is a rule-based methodology developed from human knowledge in the form of fuzzy if–then rules expressed in form of statement in which some words are characterized by continuous MFs; e.g. the following is a frequently used fuzzy *if–then* rule in risk assessment (An *et al*, 2007).

If failure probability (FP) is *high* AND consequence severity (CS) is *severe*, then risk level (RL) of the failure event is *major*.

Here, FP, CS, and RL are linguistic variables while *high, severe* and *major* are linguistic terms characterised by MFs.

A fuzzy rule base consists of a set of fuzzy *if–then* rules. Consider the input space $U = U_1 \times U_2 \times ...... \times U_n \subset R^n$ and the output space $V \subset R$. Only the multi-input–single-output case is considered here, as a multi-output system can always be decomposed into a collection of single-output systems. To be precise, a. fuzzy rule base comprises the following fuzzy *if–then* rules (Bojadziev & Bojadziev, 1995):

$$R_i : if\ x_1\ is\ A_1^i\ and...and.x_n\ is\ A_n^i,.then\ y\ is\ B^i \qquad (5\text{-}4)$$

where $A_j^i (i = 1,.2,...r;\ \mathrm{j} = 1,.2,...\mathrm{n})$ is the *i-th* linguistic terms in the *j-th* part of the antecedent, *r* is the number of linguistic terms of a linguistic variable in the antecedent. *n* is the number of linguistic variable, A_1^i and B^i are the fuzzy sets in $U \subset R$ and $V \subset R$, respectively, and $x = (x_1, x_2, ...x_x)^T \in U$ and $y \in V$ are the input and output (linguistic) variables of the fuzzy reasoning system respectively. However, due to the concise nature of fuzzy *if–then* rules, they are often employed to capture the imprecise modes of reasoning that play an essential role in the human ability to make decisions in an environment of uncertainty and imprecision. Therefore, in the proposed fuzzy reasoning system, human knowledge has to be represented in the form of the fuzzy *if–then* rules i.e. expressed in Equation (5-4). There are three major properties of fuzzy rules that are outlined as follows (An *et al*, 2007).

1. A set of fuzzy *if–then* rules is complete only if for any $x \subset U$, there is at least one rule in the fuzzy rule base, say rule R_i as in the form of equation (5-4), thus:

$$\mu_{A_1^i}(x) \neq 0 \qquad (5\text{-}5)$$

for all $i = 1,.2,...,.n$. Intuitively, the completeness of a set of rules means that at any point in the input space, there is at least one rule that ‘fires’, i.e. the membership value of the *if* part of the rule at this point is non-zero.

2. A set of fuzzy *if–then* rules is consistent if there are no rules with the same *if* parts, but different *then* parts.

3. A set of fuzzy *if–then* rules is continuous if there do not exist such neighbouring rules whose *then* part fuzzy sets have empty intersection, i.e. they do not intersect.

5.2.1.1 Fuzzy inference system (FIS)

The FIS consists of four steps which are the *fuzzy rule base, fuzzification, fuzzy inference engine*, and *defuzzification* as described in the followings.

1 Fuzzy rule base

Construction of these rules involves the deployment of various knowledge acquisition techniques to generate appropriate information required for the development of fuzzy linguistic variables and their associated MFs in order to determine the corresponding risk levels (RLs). This gathering of the required information can be achieved through the deployment of several techniques; however, knowledge acquisition techniques to be applied in this research are as enumerated below (An *et al*, 2006);

(a) historical data analysis;

(b) failure analysis;

(c) concept mapping;

(d) domain of human expert experience and engineering knowledge analysis.

The above mentioned techniques are not mutually exclusive thus their combination is found to be the most effective way of determining the rule base (An *et al*, 2007).

2 Fuzzification

This process involves the conversion of input values into the corresponding fuzzy MF values. This is a stage where the degrees of input values belonging to each of the appropriate fuzzy sets by MFs are determined.

3 Fuzzy inference engine

This is a process where the principles of fuzzy logic are deployed by combining the fuzzy *if–then* rules in the fuzzy rule base into a mapping from input fuzzy sets to an output fuzzy set. Fuzzy inference engine consists of three steps which are *evaluation of fuzzy rules, implication,* and *aggregation.* These steps are described in the following sections.

Step I -Fuzzy rule evaluation: Evaluation of fuzzy rules is conducted to determine which rule in the rule base is fired or not through the application of fuzzy logic principles to combine fuzzy *if–then* rules in fuzzy rule base into a mapping for example from a fuzzy set A and U to a fuzzy set B in V. Following the fuzzification of inputs, these fuzzified values are applied to each rule to determine whether the rule will be fired. If a rule has a true value in its antecedent (input part), it will be fired and then contribute to the consequent (output part). If the antecedent of a given rule has more than one part, the fuzzy operator will then be applied to evaluate the composite firing strength of the rule for example assume an *i-th* rule has two parts its antecedent or input part (An *et al*, 2006 & 2007).

$$R_i : if\ x_1\ is\ A_1^i\ and \ldots x_2\ is\ A_2^i, \ldots\ldots then\ y\ is\ B^i \quad (5\text{-}6)$$

where $i = 1,.2,...,.r$

The two parts in the antecedent are connected with '*and*' and the firing strength α_i can be obtained using fuzzy intersection (minimum) operation;

$$\alpha_i = \min\{\mu_{A_1^i}(x_1), \mu_{A_2^i}(x_2)\} \tag{5-7}$$

where $\mu_{A_1^i}(x_1)$ and $\mu_{A_2^i}(x_2)$ are the membership functions (MFs) of fuzzy sets A_1^i and A_2^i. The firing strength is implicated with the value of the conclusion MF to produce an output in form of a truncated fuzzy set.

Step II -Fuzzy rule implication process: The implication using fuzzy intersection (minimum) operation is given by;

$$\mu_{imp^i}(y) = \min\{\alpha_i, \mu_{B^i}(y)\} \tag{5-8}$$

where $\mu_{B^i}(y)$ is the MF of the conclusion part of a fuzzy rule and $\mu_{imp^i}(y)$ is the MF of the truncated fuzzy set after implication. The truncated fuzzy sets that represent the implication outputs of each rule are aggregated into a single fuzzy set.

Step III -Fuzzy aggregation process: The aggregation using fuzzy union (maximum) operation is denoted by;

$$\mu_{agg}(y) = \max\{\mu_{imp^1}(y), \mu_{imp^2}(y), \mu_{imp^r}(y)\} \tag{5-9}$$

where $\mu_{agg}(y)$ is the MF of the fuzzy set after aggregation.

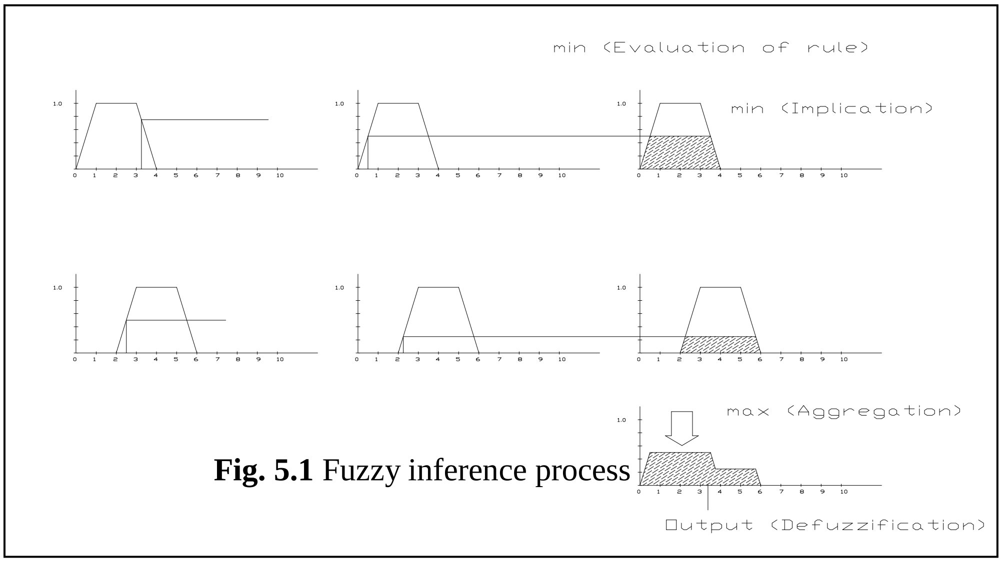

Fig. 5.1 Fuzzy inference process

5.2.1.2 Defuzzification

The aggregate output fuzzy set is used as input for the defuzzification process to obtain an output in a single number. This single number is in a crisp form, representing the final result of the fuzzy inference process. To obtain this value the centroid of area method which is the most frequently used method in fuzzy reasoning systems is used to determine the centre of gravity of an aggregated fuzzy set, which is defined and denoted as in Equation (5-10) or (5-11);

$$y_{def} = \frac{\int_y y_1 u_{agg}(y)dy}{\int_y u_{agg}(y)dy} \tag{5-10}$$

where $\mu_{agg}(y)$ is the aggregated output MF. The process of fuzzy inference is shown in Fig.5.1. The above Equation (5-10) can be expressed in a more discrete form as in Equation (5-11) below;

$$y_{def} = \frac{\sum_{i=1}^{n} y_i u_{agg}(y_i)}{\sum_{i=1}^{n} u_{agg}(y_i)} \tag{5-11}$$

where;

n = the number of aggregated risk level conclusions

y_i = the support value at which the *i-th* membership function reaches its maximum value

$u_{agg}(y_i)$ = the degree of truth of the *i-th* membership function

y_{def} = the Weighted Mean value of Maximum conclusion

5.2.2 Advantages and disadvantages of fuzzy reasoning approach

In contrast with the traditional methods mentioned earlier, the fuzzy logic reasoning approach has the following advantages (An *et al*, 2000a & 2007):

5.2.2.1 Advantages

- It has the ability to integrate expert knowledge, engineering judgement, historical data and other risk analysis information to handle the safety and risk assessment in a more consistent manner;
- It can make use of ambiguous, imprecise, incomplete and uncertainty information in the assessment;
- The risk can simply be evaluated using the linguistic expressions which are employed in conducting risk assessment;
- It offers a more flexible structure for combining failure occurrence and consequence.

5.2.2.2 Disadvantages

Possible human error arising from actions of risk analysts will affect the results

5.3 Two Parameters Risk Assessment Method (TPRAM)

TPRAM is a fuzzy reasoning approach (FRA) based risk assessment method. This method combines two risk factors such as frequency or probability of failure occurrence and the severity of failure consequence in order to determine the risk level.

However, it is pertinent to note that these two risk factors can be generated through the use of other traditional methods. Therefore, combining them together in a single assessment process will even ensure more reliable results. Failure occurrence probability can be computed as an output of other methods like event tree analysis, fault tree analysis etc. to quantify failure during the process time, while the failure consequence severity is ranked subjectively according to the seriousness of the failure event. Generally, the failure frequency can be determined by quantitative approaches and the consequence severity by some highly subjective means. Therefore to determine the consequence severity of a failure will require the employment of subjective methods like previous experience or expert judgement or engineering judgement.

The above therefore, suggests the need for methods which can effectively combine both quantified and qualified (subjective) safety information to determine the risk level. This need led to the development of method or methods based on the principles of fuzzy reasoning approach (FRA). As stated earlier FRA has the ability to process incomplete safety information, imprecise knowledge and subjective information such using methods as TPRAM.

It is obvious that, TPRAM provides a more effective and efficient way of assessing risk with high level of uncertainties. This method employs principles of FRA through the use of fuzzy inference system (FIS) where the failure frequency and consequence severity are described in linguistic terms. These linguistic variables are fuzzified to determine their degrees of membership. These membership functions (MFs) are then evaluated using linguistic rule base and fuzzy logic operations to establish the corresponding degree of membership in each risk class. These fuzzy conclusions are then defuzzified to obtain a single crisp value representing the risk level for the failure which is usually expressed as a percentage belief.

In this work, this method will be modified to develop the proposed knowledge-based modeling process for assessing offshore platform related risks.

5.4 Knowledge-based Concept Framework

As mentioned in the previous sections, the proposed knowledge-based modelling is a composite (Knowledge-based) framework shown in Figure 5.2. This is designed to introduce a simple schematic arrangement on how concepts of fuzzy reasoning based approach has been integrated with the concept of design for safety in order to facilitate identification process for all possible cut sets leading to top events. This process ensures that all identified cut sets are put into focus, and the uncertainties associated with them are also adequately dealt with to achieve a more efficient risk assessment through the design process of offshore platform. More details of this modelling process are discussed in Chapter 6.

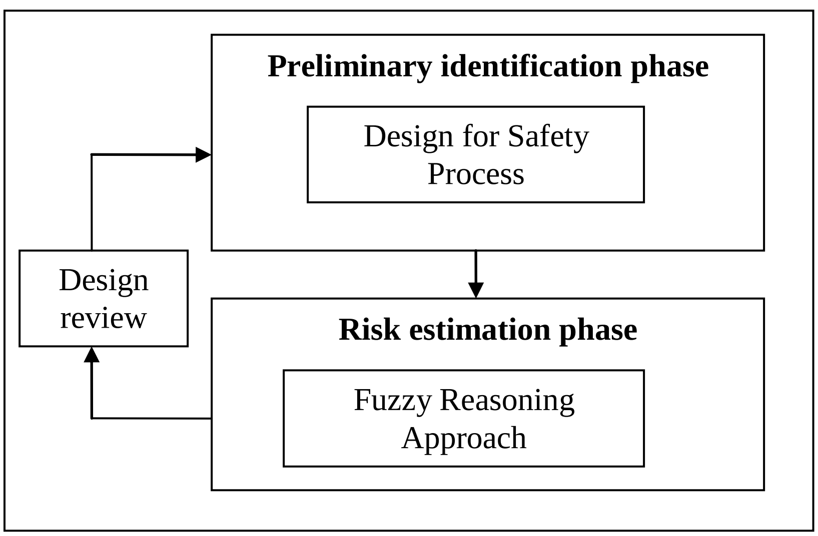

Fig. 5.2 Knowledge-based framework

5.4.1 Preliminary Identification Phase

This phase is dedicated to the deployment of techniques for the identification of causes leading to the top events based on the principles of design for safety. In other words this can be referred to as design for safety phase of the Knowledge-based modelling framework being developed for the risk assessment.

The process requires experienced system operators and engineers to participate as a means of ensuring proper identification of all potential failure events. This process is based on detailed assessment of effects of such failures on the system safety and performance.

At this stage, some traditional safety analysis methods may possibly be deployed to compliment the identification efforts for all the potential system risks, which have been discussed earlier in this Chapter.

5.4.2 Estimation Phase

Risk estimation is the conclusive risk characterisation phase which is finally expressed mostly in qualitative term. This phase is designed based on the principles of fuzzy reasoning approach. The process involves gathering of information on the frequency of the likelihood of occurrence of each identified failure event, its possible consequences, and probability that consequence will result. The information gathered at this stage will be used to establish risk parameters which will provide all the necessary input for further analysis based on the principles of fuzzy reasoning approach (FRA), more detailed discussion will be given in Chapter 6.

However, due to the high level of uncertainty in the available data, the risk analysis should combine quantitative methods in the safety analysis process, with other tested analysis methods like fuzzy reasoning which has been proved to be most suitable especially in dealing with subjectivities. The results obtained at this stage will provide basis for risk evaluation and design review and/or recommendation of responses to the evaluated risks. The information gathered from this process will be used to determine priority action regarding possible condition in relation to system safety.

5.4.3 Design review

Design review involves a systematic examination of the design process with the aim of meeting design requirements. This can be conducted at any stage of the design process in order to eliminate or reduce the risk to as low as reasonably practicable (ALARP). The performance of this process may be determined by the result produced at various stages of risk estimation phase.

5.5 Summary

Considering earlier reviews in the previous Chapters on some traditional methods which could be used to analyse the data where even for example failure mode effect analysis (FMEA) being one of the most efficient is found to be weak in dealing with multiple relationships between failure modes, causes and effects. The database could be more 'reliable' if repeat entries were eliminated with many-to-many relationships among several FMEA elements. This suggests the need for adoption of other alternatives such as combining some compatible attribute of the traditional methods with concept of design for safety and fuzzy reasoning approach in order to fill the gap created by observed weakness.

Fuzzy reasoning approach encourages the performance of analysis based on prioritising the identified failures obtained using other methods. This result enables appropriate actions to correct or mitigate the effects of a failure to be prioritised even though the information is vague, ambiguous, qualitative or imprecise.

In this chapter, the fundamentals of fuzzy reasoning approach (FRA) has been discussed, its advantages enumerated based on which the basis for developing a combine framework with other traditional method was established. This framework combines the advantages of the concept of design for safety with that of the fuzzy reasoning approach to develop a new knowledge-based model for the risk assessment for offshore platform.

Also discussed in this Chapter is the FRA based method referred to as two parameter risk assessment method (TPRAM). This method will be modified further to develop a knowledge-based risk assessment model to be proposed in this research work and eventually the two methods will be compared to establish the effect of modification via results and eventual decision-making. Details on the new knowledge-based risk assessment model are discussed in Chapter 6.

CHAPTER 6

Knowledge-Based Risk Assessment Technique

This Chapter details the development of the proposed knowledge-based risk assessment technique KBRAM which is a risk assessment technique developed for application in the identification and assessment of risks associated with an offshore platform. It consists of a risk analysis method based on the concept of design for safety and the principle of fuzzy reasoning approach (FRA). The technique begins with the establishment of foundation based on safety needs, where limitations associated with some of the traditional safety assessments techniques are highlighted in relation to the quality and quantity of information. The Chapter concludes with discussion on the method's main attributes and innovations tailored towards effective assessment of offshore platform associated risks.

6.1 Introduction

The offshore oil and gas industry is associated with, risks as enumerated in Chapter 1. These risks sometime lead to failures with varying consequences ranging from system deterioration and/or malfunction as well as possible injuries to persons and environmental degradation (Khan *et al,* 2002). Due to the nature of risk which is mostly controlled by numerous factors such as human error it is difficult to conduct risk analysis at the early stages of the project. The nature of data and availability of information in most circumstances, which make it extremely difficult to adequately assess risks associated with an offshore system due to the level of uncertainty involved. The various risk assessment techniques currently being used in the industry such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Failure Mode and Effects Analysis (FMEA) etc are comparatively effective and their results also reliable. However, their applications have been limited due sometimes to difficulties in obtaining information of high quality and/or sufficiency as a pre-requisite requirement to guarantee their effective applications within the industry (Crawley & Grant, 1997). Furthermore, these quantitative techniques have been found to be deficient in dealing with uncertainties and subjectivities associated with safety and risk data. These facts necessitate the need for continuous search for new or improved risk analysis technique for the purposes of identification and assessment of offshore facility associated risks. This further gives credence to the need for a more effective way to process risk information and reliably apply same findings through the design in order to facilitate decision-making and eventual approvals.

The knowledge based safety model is proposed to provide alternative for decision-making through a safe design process. This knowledge based risk assessment model is a modified safety management framework comprising five phases, such as problem definition phase, data collection and analysis phase, risk identification phase; risk estimation phase and risk response phase. The process provides a systematic approach to the identification and control of high-risk areas. Figure 6.1 shows the typical steps of the proposed risk assessment process. This framework is considered to be generally applicable to most risk analysis processes for offshore platforms. However, some variations may be applied depending on circumstances where there may be need for complete elimination of some steps (An *et al*, 2007). The definition of safety problems is conducted using the concept of design for safety technique while fuzzy reasoning approach is applied for the analysis of the risks, i.e. risk identification, assessment, and control. The background and the steps considered in this assessment method are elaborated in the subsequent sections.

6.2 Development of a Knowledge-Based Risk Assessment Model

As discussed earlier in this report, design for safety as a process relies on proper examination of the procedures to enable identification and assessment of potential hazardous events and their associated risks with regard to the chosen system in order to provide rational basis for determining where and when to apply risk reduction and/or control measures appropriately. An effective risk analysis process must cover all aspects of risks through the various steps in the design process in order to reach rational decision regarding appropriate steps needed to minimise, reduce or even eliminate the risk involved. Therefore, this must include sufficient particulars to demonstrate that hazards with the potentials to cause the system failure are identified, evaluated, and appropriate measures applied to bring the level of risks to As Low As Reasonably Practicable (ALARP) (An *et al* 2003a & 2003b).

This proposed risk analysis model begins with the identification of safety need for the system following the collation of the relevant information from previous records i.e. database incidents and accidents on similar systems. The overall safety need is defined with reference to statutory regulations, the product deterministic life, and various system failure events as well as possible resultant consequences. However, for design with such complexities like an offshore platform and its accompanying insufficient and/or vague risk information, the use of expert judgement becomes necessary in order to adequately determine the safety need and conclude with the choice of the top events. The top event is then further analysed through progressive steps from component to sub-system and finally to system levels (Umar *et al*, 2006).

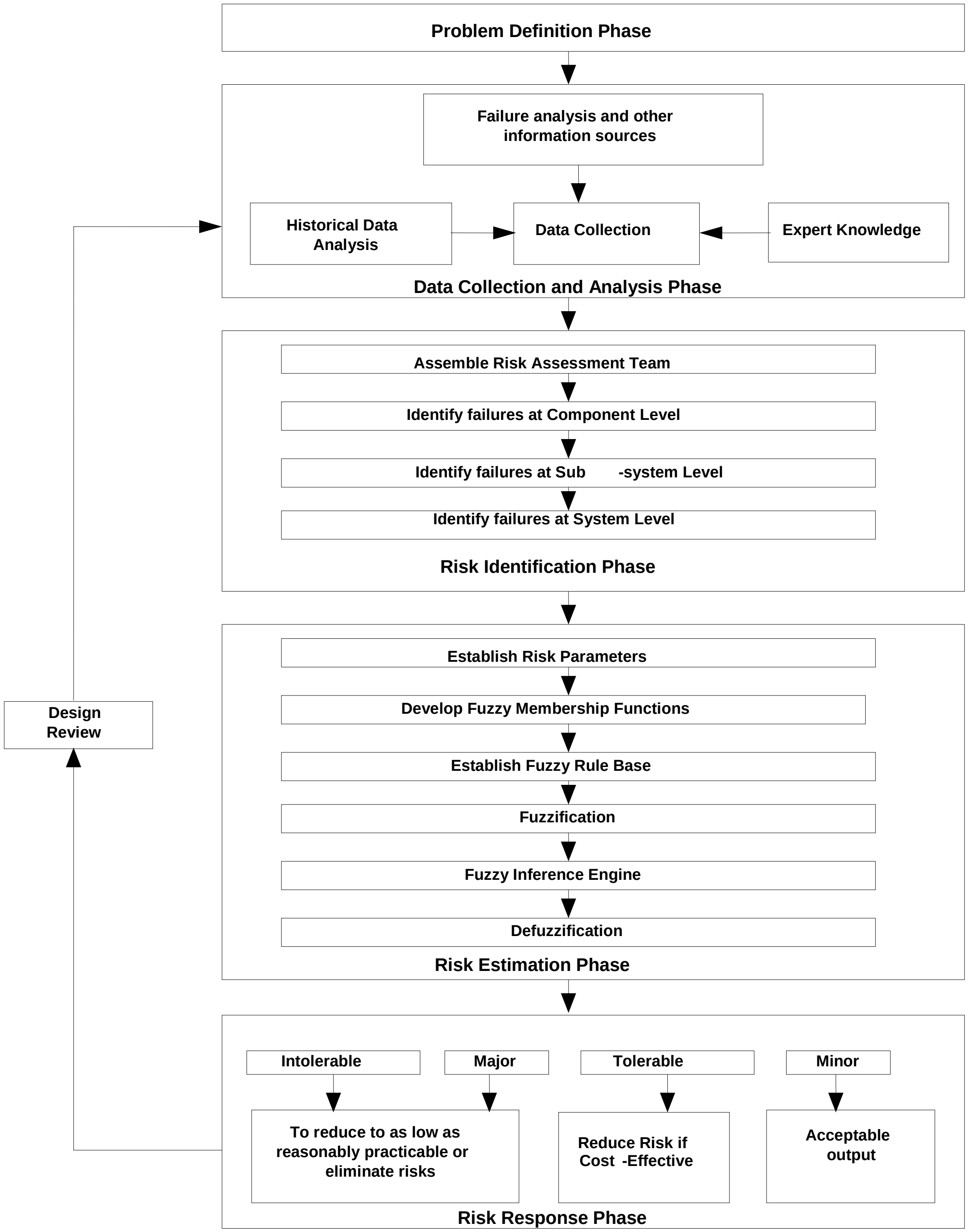

Fig. 6.1 Proposed knowledge-based risk assessment model

6.2.1 Problem definition phase

Risk assessment begins with identification of safety needs while problem definition involves identifying specific safety requirements. These requirements should be specified possibly at different levels, e.g. component level, sub-system level and the offshore system level. The following typical items may need to be specified in the problem definition (An *et al*, 2006; BS EN ISO 14001, 2004; BS EN ISO 9000 2005; BS EN ISO 20815, 2008; IEC 62278, 2008; EN50129, 1998).

1. Sets of rules and standard regulations made by the regulatory authorities and classification societies, e.g. Health & Safety Executive etc
2. Deterministic requirements for safety, reliability, availability, maintainability, etc.
3. Criteria referring to probability of occurrence of serious hazardous events and the possible consequences.

6.2.2 Data collection and analysis phase

Once the need for safety is established, the risk assessment progresses from the problem definition phase to the data collection and analysis phase with the aim of developing a good understanding of what constitute serious accidents and incidents in a particular offshore system over the years to generate information. If the statistical data is not available, expert and engineering judgements could be applied.

The information generated at this stage will then be used to develop qualitative descriptors and associated MFs. A number of the most commonly used techniques can be used to gather information and knowledge such as statistical data and information analysis, domain human experience and engineering knowledge analysis and concept mapping. These techniques can also be combined to generate sufficient risk information in the most effective way. The information generated at this stage will be applied to conduct the process of risk identification.

6.2.3 Risk identification phase

The aim of risk identification process is to enable systematic identification of all potential hazardous events associated with a chosen system of the offshore platform at different levels, e.g. from component level to sub-system level with a view to assessing their effects on the entire offshore system safety. At this stage several risks identification methods such as brainstorming approach, check-list, 'what if?', HAZOP (Hazard and Operability), and failure mode and effect analysis (FMEA), may be deployed either individually or in combination to identify the potential hazardous events of a particular offshore system. The risk identification can be initially conducted to identify component hazards, before progressing up to sub-system level and finally to the offshore system level. At this stage also a team of risk experts with pre-requisite knowledge will be assembled to assess and determine the risk scores for failure consequence severity (FCS) and failure consequence probability (FCP) based on their knowledge and experiences of the system being assessed.

6.2.3.1 Assemble risk assessment team

To accomplish the above task a team of experts with varying knowledge and experiences needs to be nominated and assembled. These experts are from different background thus will have different impacts on the final decision, therefore weighted factor (WF) is introduced into the risk assessment process. These factors will be assigned to reflect their knowledge, experience, and competences in dealing with the chosen system. WFs assigned these experts would be applied in line with the principles of fuzzy reasoning approach (FRA) where the sum total of all the WF must be equal to 1, expressed as $\sum WF = 1$ where aggregated score of a failure event (FS) is within the range between 0 and 1 which is represented by $FS \in [0,1]$. This will be done before the commencement of risk assessment process so as to ensure all the three parameters have crisp single inputs for all the failure events ready for the conduct of risk estimation.

6.2.4 Risk estimation phase

Risk estimation phase is where the RLs are assessed at component level, sub-system level and the implication on the entire system and this can be carried out either on qualitative or quantitative basis. Various risk analysis techniques such as fault tree analysis, event tree analysis, failure modes and effect analysis (FMEA), programme evaluation and review technique that are applicable across sectors, are currently used in the offshore oil and gas industry. As stated earlier in this report, in some instances it may be extremely difficult to conduct a quantitative risk assessment due to the high level of uncertainty involved in the risk data. However, even with such level uncertainty, subjective risk analysis based on the expert knowledge applied through the principles of fuzzy reasoning approach (FRA) incorporated into modeling may prove to be more effective and suitable for estimating associated risks. In this report risk estimation is made up of six stages which are described in details in the following sections.

6.2.4.1 Establishment of risk parameters

Three risk parameters are used in this proposed risk assessment model to assess risk levels (RLs) of component failure events and their implication on the sub-systems and overall system (offshore platform). The aim at this stage is to determine the risk level of identified failure events. It is worth noting that, the overall RL is usually determined through the assessment using two fundamental input parameters i.e. failure frequency (FF) and consequence severity (CS) (An *et* *al*, 2007). However, in this study a third parameter consequence probability (CP) has been introduced due to some reasons as enumerated in the next paragraph.

As mentioned earlier, in this study the two parameters will be referred to as failure likelihood (FLH), and failure consequence severity (FCS). Furthermore, considering the magnitude of a particular failure, risk is highly dependent on several factors, such as product nature, equipment reliability, human reliability, and work environment; the two input parameters may require some modification in order to achieve much more detailed estimation of risk levels (RLs) at all levels. Consequently, a third parameter of failure consequence probability (FCP) has been introduced in order to capture the possibilities of consequence resulting upon occurrence of any particular failure event. The third risk parameter is introduced to generate additional experts' opinion on the failure risks associated with the offshore platform as a means of achieving further reduction in the level of subjectivities in the risk information for more reliable results. This third parameter became necessary when one consider an example of smoke in a building as enumerated below;

Assume a building has a higher number of smokers and compare risk estimation using two scenarios;

Scenario 1- 2 Parameter: fire likelihood is HIGH and consequence severity is HIGH therefore, the risk level will be estimated to be HIGH

Scenario 2- 3 Parameter: fire likelihood is HIGH and consequence severity is HIGH and consequence probability is adjudged LOW then the risk level will certainly be downgraded to MEDIUM

In addition to the above efforts, the experts' contribution would also be evaluated through appropriate processes such as brainstorming, checklist, and scoring (An *et al*, 2000a).

The FLH defines the number of times an event occurs over a specified period, e.g. number of events/year. FCS indicates the number of fatalities, major injuries and minor injuries resulting from the occurrence of a particular failure event. This proposed risk model as discussed in Chapter 5 is based on principles of FRA method to enable processing of incomplete risk data, imprecise knowledge and subjective information to be used in the risk assessment process. As stated earlier in this report, risk data and information can be obtained from a number of available sources such as previous accident and incident reports, historical data, engineering knowledge and expert experience to conduct the risk assessment. Risk identification can be conducted earlier to enable identification of potential failure events, which are grouped into a number of categories based on their contributions to the safety. For example, an offshore platform processing unit is faced with major inherent hazards such as fire and explosion depending on the location of the sub-systems and the nature of the product being processed. Each sub-system is faced with a number of components failure events, e.g. a leak in the compressor may lead to continuous flow of flammable gas which on ignition would cause a jet fire and may eventually cause injury or fatality, equipment damage, environmental degradation etc. Thus risk assessment need be carried out from component failure level, to sub-system level and finally to offshore processing system level. To analyse the risk associated with, for example an offshore processing unit, the fuzzy reasoning approach (FRA) with three input parameters described in the previous sections would be applied from the component failure events and their cumulative effects at the sub-system level to determine the overall RL and its implication on the entire system level (An *et al*, 2000a).

An *et al*, (2007) stated that the application of FRA in risk assessment may have the following advantages;

1. the risk can be evaluated directly by using qualitative descriptors;
2. it is tolerant of imprecise data and ambiguous information;
3. it gives a more flexible structure for combining qualitative as well as quantitative information.

FRA uses qualitative descriptors in natural language to provide basis for approximate reasoning with imprecise propositions. Qualitative descriptors can be used to represent the condition of a risk factor at a given interval, and the details of fundamentals of FRA are as discussed in Chapter 5. However, the proposed risk assessment model which adopts the principles of FRA begins with the development of fuzzy qualitative descriptors and MFs for describing FLH, FCS, FCP and RL expressions, as summarised in the following sections.

1. Failure likelihood FLH

Table 6.1 describes the range of the FLH to estimate likelihood by using such qualitative descriptors as ‘Very low’, ‘Low’, ‘Average’, ‘High’, and ‘Very high’ suggested to be less than 6E-06, between 3-12E-06, 9-21E-06, 18-27E-06 and 24-30E-06 respectively as shown in Table 6.2. The trapezoidal membership functions (MFs) are assigned to describe these MFs of the likelihood of occurrence as shown in Figure 6.2 and each qualitative descriptor of FLH has categorisations which describe the levels of likelihood in quantitative terms. For example, qualitative descriptor ‘Very low’ is defined to cover the range of FLH between non-occurrence which is 0 and 6E-06, and the approximate numerical value can be computed to be a maximum of 0.06 event per year.

Table 6.1 Failure Likelihood

Linguistic variables	**Failure likelihood probability description**	**Failure frequency** $x10^{-6}$
Very low	Failure unlikely to be noticed or even occur.	0-6
Low	Failure likely to occur, but unlikely to be frequent.	3-12
Average	Failure likely to occur more than once.	9-21
High	Failure almost certain to occur at least once.	18-27
Very high	Failure is certain to occur several times.	24-30

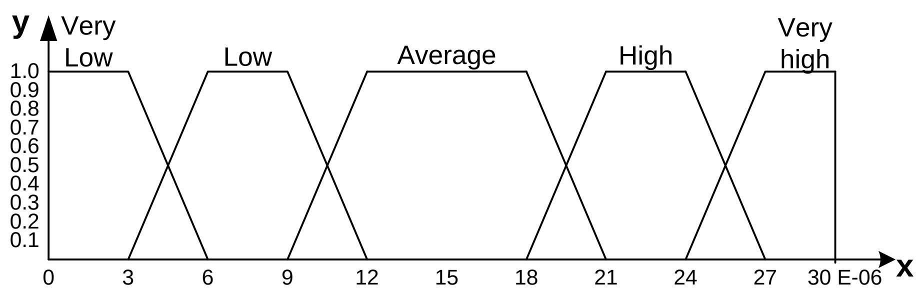

Fig. 6.2 Membership functions of Failure Likelihood

2. Failure consequence severity FCS

The FCS describes the magnitude of possible consequences and qualitative descriptors such as '*Negligible', 'Marginal', 'Moderate', 'Severe'* and *'Catastrophic'* are used to describe the different linguistic terms. Table 6.2 shows the criteria used to rank the FCS of failure events while the MFs of FCS are as shown in Figure 6 3.

Table 6.2 Failure Consequence Severity

Linguistic variables	**Failure consequence severity description**	**Score Range**
Negligible	Failure has no effect on the system operation, the operator may not even notice.	0-2
Marginal	Failure that would cause slight annoyance to the operator but not result in system deterioration.	1-4
Moderate	Failure that would cause high degree of operator dissatisfaction or result in noticeable but slight system deterioration.	3-7
Severe	Failure that would cause significant deterioration in system performance and/or lead to minor injuries.	6-9
Catastrophic	Failure that would seriously affect the ability to complete	8-10

	the task or cause damage, and/or lead to injuries or even death.	

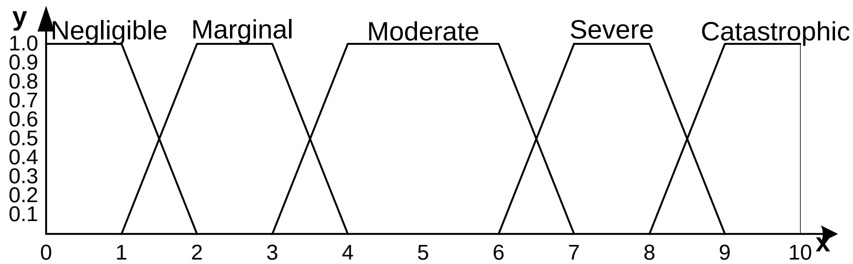

Fig. 6.3 Membership functions of Failure Consequence Severity

3. Failure consequence probability FCP

The third input parameter FCP describes the magnitude of possibility of consequences occurrence following a failure event. Qualitative descriptors such as *'Highly unlikely', 'Unlikely', 'Likely', 'Highly likely'* and *'Definite'* are used to describe the different linguistic terms. Table 6.3 shows the criteria used to rank the FCP of failure events and the MFs of FCP are shown in Figure 6 4.

Table 6.3 Failure Consequence Probability

Linguistic variables	**Failure consequence probability description**	**Score Range**
Highly unlikely	Failure consequence is a remote possibility.	0-2
Unlikely	Consequence is not likely but possible given the occurrence of failure event.	1-4
Likely	A potential consequence may result.	3-7
Highly likely	A high potential consequence will result with failure occurrence.	6-9
Definite	Consequence is certain to result given the failure event occurrence.	8-10

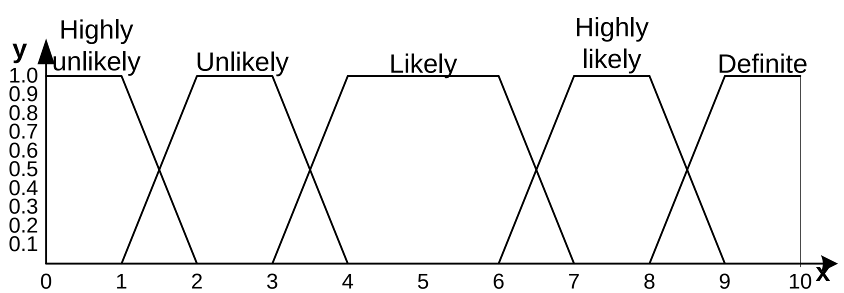

Fig. 6.4 Membership functions of Failure Consequence Probability

4. Risk level RL

RL commonly can be expressed in terms of degrees of belonging within ranges of qualitative descriptors such as, *'Minor', 'Tolerable', 'Major'* and *'Intolerable'*, that are referred to as risk expressions. Table 6.4 shows the qualitative descriptor categories of RL. Trapezoidal MFs are also employed to describe each qualitative descriptor of RL as shown in Figure 6.5.

Table 6.4 Risk level

Linguistic variables	**Risk level**	**Risk scores**
Minor	Acceptable risk no attention required.	0-3
Tolerable	Further reduction required depending on cost.	2-6
Major	Require reduction to as low as reasonably practicable	5-9
Intolerable	Must be reduced.	8-10

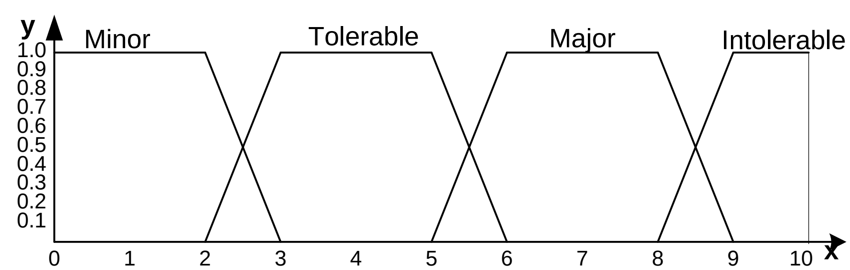

Fig. 6.5 Membership functions of Risk level

6.2.4.2 Development of fuzzy rule base

Fuzzy rule base consists of a set of fuzzy IF–THEN rules. This is the main focal point of a fuzzy logic system as all other operations are channeled towards implementation of these rules in a reasonable and efficient manner. It comprises of the following fuzzy IF–THEN rules as detailed in Chapter 5.

For example, in the proposed offshore platform risk analysis model, a rule with three input parameters can be constructed and interpreted as *IF* FLH is very low *and* FCS is severe *and* FCP is likely, *THEN* RL is tolerable, where 'very low', 'severe', 'likely' and 'tolerable' are qualitative descriptors characterized by MFs and their corresponding quantitative values which will be used to express percentage belief in membership.

As described in the works of both An *et al,* (2007) and Zeng *et al,* (2006), fuzzy rules are expressed in qualitative descriptors rather than numerical values, they present a natural platform for the delivery of information based on expert knowledge and engineering judgments. Therefore, experts often find it very convenient to express their knowledge in assessing risks. Though other factors also need to be considered in constructing the fuzzy rules base as enumerated in An *et al* (2006), where the factors influencing the development of fuzzy rule are given as below:

(a) Completeness: the fuzzy rule base must cover all matches between inputs and outputs;

(b) The number of rules: although there is no general procedure for deciding the optimal number of rules, the decision is important when performance, efficiency of computations and choice of qualitative descriptors are important considerations;

(c) Consistency and correctness: the choice of fuzzy rule should minimize the possibility of contradiction, and unwanted interactions between the rules.

The membership function (MF) mapped out is used to establish the fuzzy rules and the total number of these rules in the fuzzy rule base depend on the number of qualitative descriptors adopted for representing input parameters which in this case are FLH, FCS and FCP. These input parameters have five qualitative descriptors each, thus the number of rules (NR) in the fuzzy rule base will be computed as ($NR=5 \times 5 \times 5 = 125$) as shown in Table 6.5. Furthermore, these MFs are interpreted to obtain results of their implications according to the fuzzy rules using a combination of Microsoft (MS) Excel and AutoCAD programmes. The mappings in AutoCAD programme adopted as a rule viewer were used to access the MFs. Fuzzy inference functions such as fuzzification, aggregation and defuzzification processes.

6.2.4.3 Determine expert weighted scores at component (failure event) level

Members of the risk assessment group will then be required to allocate scores to each failure event at component level for only two out of the three input parameters which are FCS and FCP as the information regarding the first input parameter FLH will be obtained from the industry database.

Table 6.5 Fuzzy rules

Rule No	Rule Description
R1	IF FLH is Very low and FCS is Negligible and FCP is Highly unlikely THEN RL is Minor
R2	IF FLH is Very low and FCS is Marginal and FCP is Highly unlikely THEN RL is Minor
R3	IF FLH is Very low and FCS is Moderate and FCP is Highly unlikely THEN RL is Minor
R4	IF FLH is Very low and FCS is Severe and FCP is Highly unlikely THEN RL is Minor
R5	IF FLH is Very low and FCS is Catastrophic and FCP is Highly unlikely THEN RL is Minor
R6	IF FLH is Low and FCS is Negligible and FCP is Highly unlikely THEN RL is Minor
R7	IF FLH is Low and FCS is Marginal and FCP is Highly unlikely THEN RL is Minor
R8	IF FLH is Low and FCS is Moderate and FCP is Highly unlikely THEN RL is Minor
R9	IF FLH is Low and FCS is Severe and FCP is Highly unlikely THEN RL is Minor
R10	IF FLH is Low and FCS is Catastrophic and FCP is Highly unlikely THEN RL is Minor
R11	IF FLH is Average and FCS is Negligible and FCP is Highly unlikely THEN RL is Tolerable
R12	IF FLH is Average and FCS is Marginal and FCP is Highly unlikely THEN RL is Tolerable
R13	IF FLH is Average and FCS is Moderate and FCP is Highly unlikely THEN RL is Tolerable
R14	IF FLH is Average and FCS is Severe and FCP is Highly unlikely THEN RL is Major
R15	IF FLH is Average and FCS is Catastrophic and FCP is Highly unlikely THEN RL is Major
R16	IF FLH is High and FCS is Negligible and FCP is Highly unlikely THEN RL is Tolerable
R17	IF FLH is High and FCS is Marginal and FCP is Highly unlikely THEN RL is Major
R18	IF FLH is High and FCS is Moderate and FCP is Highly unlikely THEN RL is Major
R19	IF FLH is High and FCS is Severe and FCP is Highly unlikely THEN RL is Major
R20	IF FLH is High and FCS is Catastrophic and FCP is Highly unlikely THEN RL is Intolerable
R21	IF FLH is Very high and FCS is Negligible and FCP is Highly unlikely THEN RL is Tolerable
R22	IF FLH is Very high and FCS is Marginal and FCP is Highly unlikely THEN RL is Tolerable
R23	IF FLH is Very high and FCS is Moderate and FCP is Highly unlikely THEN RL is Major
R24	IF FLH is Very high and FCS is Severe and FCP is Highly unlikely THEN RL is Major
R25	IF FLH is Very high and FCS is Catastrophic and FCP is Highly unlikely THEN RL is Intolerable
R26	IF FLH is Very low and FCS is Negligible and FCP is Unlikely THEN RL is Minor
R27	IF FLH is Very low and FCS is Marginal and FCP is Unlikely THEN RL is Minor
R28	IF FLH is Very low and FCS is Moderate and FCP is Unlikely THEN RL is Tolerable
R29	IF FLH is Very low and FCS is Severe and FCP is Unlikely THEN RL is Tolerable
R30	IF FLH is Very low and FCS is Catastrophic and FCP is Unlikely THEN RL is Tolerable
R31	IF FLH is Low and FCS is Negligible and FCP is Unlikely THEN RL is Tolerable
R32	IF FLH is Low and FCS is Marginal and FCP is Unlikely THEN RL is Tolerable
R33	IF FLH is Low and FCS is Moderate and FCP is Unlikely THEN RL is Tolerable
R34	IF FLH is Low and FCS is Severe and FCP is Unlikely THEN RL is Tolerable
R35	F FLH is Low and FCS is Catastrophic and FCP is Unlikely THEN RL is Tolerable
R36	IF FLH is Average and FCS is Negligible and FCP is Unlikely THEN RL is Tolerable
R37	IF FLH is Average and FCS is Marginal and FCP is Unlikely THEN RL is Tolerable
R38	IF FLH is Average and FCS is Moderate and FCP is Unlikely THEN RL is Major
R39	IF FLH is Average and FCS is Severe and FCP is Unlikely THEN RL is Major
R40	IF FLH is Average and FCS is Catastrophic and FCP is Unlikely THEN RL is Intolerable
R41	IF FLH is High and FCS is Negligible and FCP is Unlikely THEN RL is Tolerable
R42	IF FLH is High and FCS is Marginal and FCP is Unlikely THEN RL is Tolerable
R43	IF FLH is High and FCS is Moderate and FCP is Unlikely THEN RL is Major
R44	IF FLH is High and FCS is Severe and FCP is Unlikely THEN RL is Intolerable
R45	IF FLH is High and FCS is Catastrophic and FCP is Unlikely THEN RL is Intolerable
R46	IF FLH is Very high and FCS is Negligible and FCP is Unlikely THEN RL is Tolerable
R47	IF FLH is Very high and FCS is Marginal and FCP is Unlikely THEN RL is Tolerable
R48	IF FLH is Very high and FCS is Moderate and FCP is Unlikely THEN RL is Major
R49	IF FLH is Very high and FCS is Severe and FCP is Unlikely THEN RL is Major
R50	IF FLH is Very high and FCS is Catastrophic and FCP is Unlikely THEN RL is Intolerable

Table 6.5 Continue

Rule No	Rule Description
R51	IF FLH is Very low and FCS is Negligible and FCP is Likely THEN RL is Tolerable
R52	IF FLH is Very low and FCS is Marginal and FCP is Likely THEN RL is Tolerable
R53	IF FLH is Very low and FCS is Moderate and FCP is Likely THEN RL is Tolerable
R54	IF FLH is Very low and FCS is Severe and FCP is Likely THEN RL is Tolerable
R55	IF FLH is Very low and FCS is Catastrophic and FCP is Likely THEN RL is Tolerable
R56	IF FLH is Low and FCS is Negligible and FCP is Likely THEN RL is Tolerable
R57	IF FLH is Low and FCS is Marginal and FCP is Likely THEN RL is Tolerable
R58	IF FLH is Low and FCS is Moderate and FCP is Likely THEN RL is Tolerable
R59	IF FLH is Low and FCS is Severe and FCP is Likely THEN RL is Major
R60	F FLH is Low and FCS is Catastrophic and FCP is Likely THEN RL is Major
R61	IF FLH is Average and FCS is Negligible and FCP is Likely THEN RL is Tolerable
R62	IF FLH is Average and FCS is Marginal and FCP is Likely THEN RL is Tolerable
R63	IF FLH is Average and FCS is Moderate and FCP is Likely THEN RL is Major
R64	IF FLH is Average and FCS is Severe and FCP is Likely THEN RL is Major
R65	IF FLH is Average and FCS is Catastrophic and FCP is Likely THEN RL is Intolerable
R66	IF FLH is High and FCS is Negligible and FCP is Likely THEN RL is Tolerable
R67	IF FLH is High and FCS is Marginal and FCP is Likely THEN RL is Tolerable
R68	IF FLH is High and FCS is Moderate and FCP is Likely THEN RL is Major
R69	IF FLH is High and FCS is Severe and FCP is Likely THEN RL is Major
R70	IF FLH is High and FCS is Catastrophic and FCP is Likely THEN RL is Intolerable
R71	IF FLH is Very high and FCS is Negligible and FCP is Likely THEN RL is Tolerable
R72	IF FLH is Very high and FCS is Marginal and FCP is Likely THEN RL is Tolerable
R73	IF FLH is Very high and FCS is Moderate and FCP is Likely THEN RL is Major
R74	IF FLH is Very high and FCS is Severe and FCP is Likely THEN RL is Major
R75	IF FLH is Very high and FCS is Catastrophic and FCP is Highly likely THEN RL is Intolerable
R76	IF FLH is Very low and FCS is Negligible and FCP is Highly likely THEN RL is Tolerable
R77	IF FLH is Very low and FCS is Marginal and FCP is Highly likely THEN RL is Tolerable
R78	IF FLH is Very low and FCS is Moderate and FCP is Highly likely THEN RL is Tolerable
R79	IF FLH is Very low and FCS is Severe and FCP is Highly likely THEN RL is Tolerable
R80	IF FLH is Very low and FCS is Catastrophic and FCP is Highly likely THEN RL is Tolerable
R81	IF FLH is Low and FCS is Negligible and FCP is Highly likely THEN RL is Tolerable
R82	IF FLH is Low and FCS is Marginal and FCP is Highly likely THEN RL is Tolerable
R83	IF FLH is Low and FCS is Moderate and FCP is Highly likely THEN RL is Major
R84	IF FLH is Low and FCS is Severe and FCP is Highly likely THEN RL is Major
R85	F FLH is Low and FCS is Catastrophic and FCP is Highly likely THEN RL is Intolerable
R86	IF FLH is Average and FCS is Negligible and FCP is Highly likely THEN RL is Tolerable
R87	IF FLH is Average and FCS is Marginal and FCP is Highly likely THEN RL is Tolerable
R88	IF FLH is Average and FCS is Moderate and FCP is Highly likely THEN RL is Major
R89	IF FLH is Average and FCS is Severe and FCP is Highly likely THEN RL is Major
R90	IF FLH is Average and FCS is Catastrophic and FCP is Highly likely THEN RL is Intolerable
R91	IF FLH is High and FCS is Negligible and FCP is Highly likely THEN RL is Tolerable
R92	IF FLH is High and FCS is Marginal and FCP is Highly likely THEN RL is Tolerable
R93	IF FLH is High and FCS is Moderate and FCP is Highly likely THEN RL is Major
R94	IF FLH is High and FCS is Severe and FCP is Highly likely THEN RL is Intolerable
R95	IF FLH is High and FCS is Catastrophic and FCP is Highly likely THEN RL is Intolerable
R96	IF FLH is Very high and FCS is Negligible and FCP is Highly likely THEN RL is Tolerable
R97	IF FLH is Very high and FCS is Marginal and FCP is Highly likely THEN RL is Tolerable
R98	IF FLH is Very high and FCS is Moderate and FCP is Highly likely THEN RL is Major
R99	IF FLH is Very high and FCS is Severe and FCP is Highly likely THEN RL is Intolerable
R100	IF FLH is Very high and FCS is Catastrophic and FCP is Highly likely THEN RL is Intolerable

Table 6.5 Continue

Rule No	Rule Description
R101	IF FLH is Very low and FCS is Negligible and FCP is Definite THEN RL is Tolerable
R102	IF FLH is Very low and FCS is Marginal and FCP is Definite THEN RL is Tolerable
R103	IF FLH is Very low and FCS is Moderate and FCP is Definite THEN RL is Major
R104	IF FLH is Very low and FCS is Severe and FCP is Definite THEN RL is Major
R105	IF FLH is Very low and FCS is Catastrophic and FCP is Definite THEN RL is Intolerable
R106	IF FLH is Low and FCS is Negligible and FCP is Definite THEN RL is Tolerable
R107	IF FLH is Low and FCS is Marginal and FCP is Definite THEN RL is Tolerable
R108	IF FLH is Low and FCS is Moderate and FCP is Definite THEN RL is Major
R109	IF FLH is Low and FCS is Severe and FCP is Definite THEN RL is Major
R110	F FLH is Low and FCS is Catastrophic and FCP is Definite THEN RL is Intolerable
R111	IF FLH is Average and FCS is Negligible and FCP is Definite THEN RL is Tolerable
R112	IF FLH is Average and FCS is Marginal and FCP is Definite THEN RL is Tolerable
R113	IF FLH is Average and FCS is Moderate and FCP is Definite THEN RL is Major
R114	IF FLH is Average and FCS is Severe and FCP is Definite THEN RL is Major
R115	IF FLH is Average and FCS is Catastrophic and FCP is Definite THEN RL is Intolerable
R116	IF FLH is High and FCS is Negligible and FCP is Definite THEN RL is Tolerable
R117	IF FLH is High and FCS is Marginal and FCP is Definite THEN RL is Tolerable
R118	IF FLH is High and FCS is Moderate and FCP is Definite THEN RL is Major
R119	IF FLH is High and FCS is Severe and FCP is Definite THEN RL is Intolerable
R120	IF FLH is High and FCS is Catastrophic and FCP is Definite THEN RL is Intolerable
R121	IF FLH is Very high and FCS is Negligible and FCP is Definite THEN RL is Tolerable
R122	IF FLH is Very high and FCS is Marginal and FCP is Definite THEN RL is Major
R123	IF FLH is Very high and FCS is Moderate and FCP is Definite THEN RL is Major
R124	IF FLH is Very high and FCS is Severe and FCP is Definite THEN RL is Intolerable
R125	IF FLH is Very high and FCS is Catastrophic and FCP is Definite THEN RL is Intolerable

To demonstrate this proposed risk assessment method, risk information will be generated through the use of questionnaire specifically designed to enable experts to allocate scores using a scale of 1–10 to represent the implication of each of the listed failure event in relation to the two input parameters of FCS and FCP. This questionnaire enables the experts to express their knowledge and engineering judgements using a combination of linguistic and numerical expressions such as *about x-numeric, close to y-numeric etc*. or deal directly with a range of values say *between a range of numbers*, where they cannot express their opinions using exact numerical value. Zeng *et al*, (2006) gave examples of such classifications as below;

- A linguistic term, e.g. ‘‘about 7’’
- A range, e.g. (3, 7)
- A scale is likely between 3 and 7
- A fuzzy number, e.g. (3, 6, 8)

The values above are still in their crisp form and can be converted into the overall weighted scores for each hazardous event using the Equation (6-1).

As different experts have different impacts on the final decision, expert factor represented by symbol (w) is therefore introduced into the offshore platform risk assessment model to distinguish individual experts' and their competences. This factor (w) will be allocated to experts on the basis of their experience, knowledge and expertise. For example assume n experts in the group, the *ith* expert E_i is assigned a contribution factor w_i where $w_i \in [0,1]$, and $w_1 + w_2 + ... + w_n = 1$. However, it is important to note that this factor (w) is flexible and can be reviewed depending on peculiarities of the topic and/or the circumstances.

$$Z_{S_j} = \frac{\sum_{i=1}^{n} w_i s_{ij}}{n} \qquad (6\text{-}1)$$

where Z_{S_j} is the weighted risk score for failure event j, n is the total number of experts, w_i is the allocated expert factor for expert i, $i = (1,.2,..,n)$, s_{ij} is the *ith* expert (E_i) score on failure event j (*jth* failure event).

The above equation will be applied to all failure (hazardous) events at the component level to obtain the risk score for application through the fuzzy inference system.

6.2.4.4 Fuzzification

Fuzzification is the process of converting input parameters such as failure likelihood (FLH), failure consequence severity (FCS) and failure consequence probability (FCP) into their fuzzy qualitative descriptors of Z_{FLH}, Z_{FCS} and Z_{FCP} respectively in order to determine the degree of belonging of each of the appropriate fuzzy set in rule base via membership function (MF) assumptions.

Step 1: *Fuzzification of (FLH)*

In this example, the component is assumed to have a recorded failure frequency equivalent to 0.028 event per year which correspond to the linguistic categorisation, belonging to *very low*, and *low* with belief of 95% (MF=0.9533) and 5% (MF=0.0467) respectively as shown in Figure 6.6.

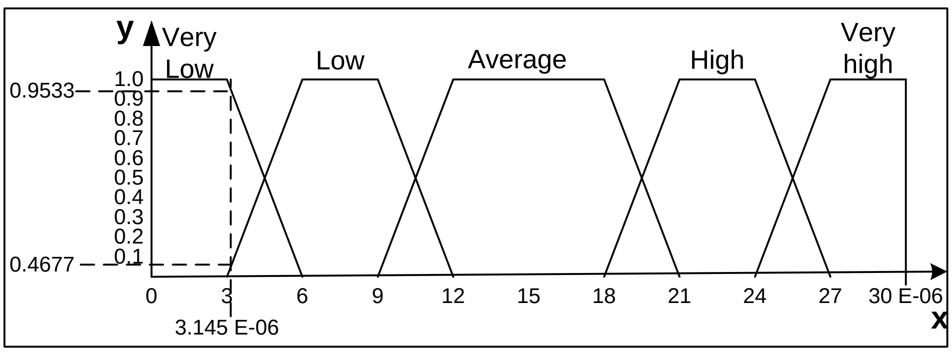

Fig. 6.6: Membership function at $Z_{FLH} = 3.15\times10^{-6}$,

Step 2*: Fuzzification of (FCS) and (FCP)*

As demonstrated in section 6.4.2.2 the input parameters of FCS and FCP, experts' weighted contributions will be applied. For example, assume three experts E_1, E_2 and E_3 in the group, their contribution factors are w_1, w_2 and w_3 respectively and their corresponding numerical values given as $w_1 = 0.5$, $w_2 = 0.3$ and $w_3 = 0.2$ $\left(\sum_{i=1}^{n} w_i = 1\right)$ assigned based on experts roles and experiences. As stated earlier, the experts have been given a range of values between 0 and 10 represented by [0, 1] for scoring the implications of failure events relative to the severity and probability that consequence will result.

i) *Fuzzification of FCS*

The consequence severity of a component failure is assumed to have experts' scores S_1, S_2 and S_3 allocated as 9, 10 and 10 respectively. Therefore, to calculate weighted experts' score for Z_{FCS}, Equation (6-1) is applied as shown below;

$$Z_{FCS} = \frac{(0.5\times 9)+(0.3\times 10)+(0.2\times 10)}{3} = \frac{9.50}{3} = 3.1667$$

The above computed score is approximately 3.20 categorised and expressed in linguistic terms, belonging to *Marginal* and *moderate* with belief of 80% (MF=0.800) and 20% (MF=0.200) respectively as shown in Figure 6.7.

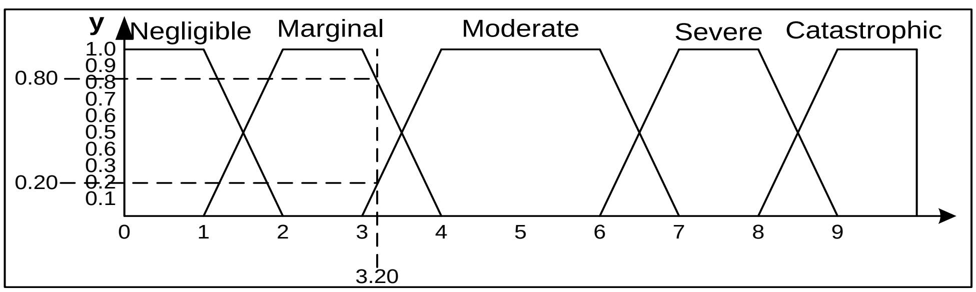

Fig. 6.7: Membership function at $T_{FCS} = 3.20$

ii) *Fuzzification of FCP*

The consequence probability of a chosen component failure is assumed to have experts scores S_1, S_2 and S_3 allocated as 5, 6 and 7 respectively. Therefore, to calculate weighted experts' score for Z_{FCP}, Equation (6-1) is applied as below;

$$Z_{FCP} = \frac{(0.5\times 5)+(0.3\times 6)+(0.2\times 7)}{3} = \frac{5.70}{3} = 1.9000$$

The above computed score return a value of 1.90 categorised and expressed in linguistic terms, belonging to *Highly unlikely*, and *unlikely* with belief of 10% (MF=0.100) and 90% (MF=0.900) respectively as shown in Figure 6.8.

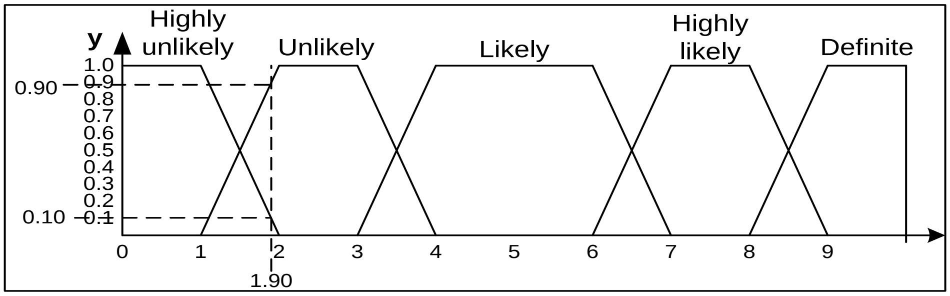

Fig. 6.8: Membership function at $T_{FCP} = 1.90$

In concluding fuzzification process fuzzy sets of the crisp values given above are expressed as $Z_{FLH} = 3.15 \times 10^{-6}$ for FLH, $Z_{FCS} = 3.20$ for FCS and $Z_{FCP} = 1.90$ for FCP. To further express the risk implication Equation (6-2) is applied and the result obtained shows the corresponding values representing the degree of their belonging (membership) according to their membership functions (MF's) as demonstrated in subsequent sections.

Figures 6.7, 6.8 & 6.9 show how the assumed values have been used to calculate the values of MF of the corresponding linguistic classification as detailed in Table 6.6. These values will then be used further to conduct fuzzy analysis of the risk.

Table 6.6 Fuzzification of inputs at $T_{FLH} = 3.15 \times 10^{-6}$, $T_{FCS} = 3.20$ and $T_{FCP} = 1.90$

Input Parameter	Linguistic class	Membership function
Failure Likelihood (FLH)	Very low	0.95
"	Low	0.05
Failure Consequence Severity (FCS)	Maginal	0.80
"	Moderate	0.20
Failure Consequence Probability (FCP)	Highly unlikely	0.10
"	Unlikely	0.90

6.2.4.5 Fuzzy inference engine

As described in Chapter 5, the proposed offshore platform risk assessment process is used to combine the fuzzy *if–then* rules in the fuzzy rule base into a mapping from input fuzzy sets representing the inputs FLH, FCS and FCP to an output fuzzy set representing output RL expression. Fuzzy inference engine consists of three stages which are *evaluation of fuzzy rules, implication,* and *aggregation.*

Stage 1: *Evaluation of fuzzy rules*

This process is primarily conducted in order to determine which rule in the rule base is fired or not, through the application of fuzzy logic principles to combine fuzzy *if–then* rules in fuzzy rule base into a mapping, for example Z_{FLH} for FLH, Z_{FCS} for FCS and Z_{FCP} Following the fuzzification of these inputs, their fuzzified values are applied to each rule to determine which of the one hundred and twenty-five (125) rules listed in Table 6.1 are fired. If a rule has a true value in its antecedent (input part), it will be fired and then contributes to the conclusion (output part). If the antecedent of a given rule has more than one part as is the case of in this study then , the fuzzy operator will then be applied to evaluate the composite firing strength of the rule, for example assume the *i-th* (2^{nd}) rule has three parts in its antecedent (An *et al*, 2006 & 2007).

According to the above eight (8) out of the one hundred and twenty-five (125) rules in the rule base have been found to be fired based on the principles described in the section above as they turn out non-zero values, see Tables 6.7 and 6.8 below;

Table 6.7 Fired rules

Rule No.	Rule Description
R2	IF FLH is Very low and FCS is Marginal and FCP is Highly unlikely THEN RL is Minor
R3	IF FLH is Very low and FCS is Moderate and FCP is Highly unlikely THEN RL is Minor
R7	IF FLH is Low and FCS is Marginal and FCP is Highly unlikelyTHEN RL is Minor
R8	IF FLH is Low and FCS is Moderate and FCP is Highly unlikelyTHEN RL is Minor
R27	IF FLH is Very low and FCS is Marginal and FCP is Unlikely THEN RL is Minor
R28	IF FLH is Very low and FCS is Moderate and FCP is Unlikely THEN RL is Tolerable
R32	IF FLH is Low and FCS is Marginal and FCP is Unlikely THEN RL is Tolerable
R33	IF FLH is Low and FCS is Moderate and FCP is Unlikely THEN RL is Tolerable

As can be seen in above, the eight fired rules will therefore be processed using fuzzy minimum operator to establish their respective firing strengths. For example to determine the corresponding firing strength of the *2-nd* rule to interpret Equation (6-2) as below;

$$\text{R2: } \alpha_2 = \min\{FLH^{Low}_{Very.low}, FCS^{Moderate}_{Marginal}, FCP^{Unlikely}_{Highly.unlkely}\} \quad (6\text{-}2)$$

= min {(***very low***, *low*), (***marginal***, *moderate*), (***highly* un*likely***, *unlikely*)}

= min {(**0.9500**, 0.0500), (**0.8000**, 0.2000), (**0.1000**, 0.9000)}

= min {(***very low***, ***moderate***, **un*likel****y)*}

= min {0.9500, 0.8000, 0.1000}

= min {(***the lowest value which is 0.100****)*}

therefore: α_2 = 0.1000

Similarly, other firing strengths of fired rules can be calculated. The results are given in Table 6.8.

Table 6.8 Fuzzy operation over fired rules

Rule No.	MF value of FLH	MF value of FCS	MF value of FCP	Firing strength
R2	0.9500	0.8000	0.1000	0.1000
R3	0.9500	0.2000	0.9000	0.2000
R7	0.0500	0.8000	0.9000	0.0500
R8	0.0500	0.2000	0.9000	0.0500
R27	0.9500	0.8000	0.1000	0.1000
R28	0.9500	0.2000	0.1000	0.2000
R32	0.0500	0.8000	0.1000	0.0500
R33	0.0500	0.2000	0.1000	0.0500

Stage II: *Implication*

The implication from antecedent to consequent can be obtained by fuzzy minimum operator method based on the firing strength of each rule. The implication output is a truncated fuzzy set. Figure 6.10 gives a detailed process of implication, where the shadowed areas indicate the output of implication for each fired rule. The firing strength for each rule is indicated in the vertical axis (degree of membership function). The linguistic variables of consequence, which is the risk level for the fired rules, are *Minor, Tolerable, Major, and Intolerable,* respectively as given in Figure 6.10.

$$\text{R2: } \beta_2 = \min\{\alpha_2, \mu_{B^2}(y)\} \tag{6-3}$$

where α_2 is the firing strength of the *2-nd* rule, $\mu_{B^2}(y)$ is the membership function (MF) of RL of the fuzzy *2-nd* rule and β_2 is the membership function of the truncated fuzzy set after the performance of implication operation on *2-nd* rule. The implication of the *2-nd* rule can be computed using Equation (6-3).

Step 1: Substitute the value of α_2 into Equation (6-3)

$$\text{R2: } = \min\{0.9500, 0.9000, 0.1000, \mu_{B^2}(y)\}$$

$$= 0.1000, \mu_{B^2}(y)\}$$

To conclude implication process the value of MF RL_{28} must be determined first and this is computed to obtain a value of 4.000 as demonstrated below;

Step 2: Find the value of $\mu_{B^2}(y)$

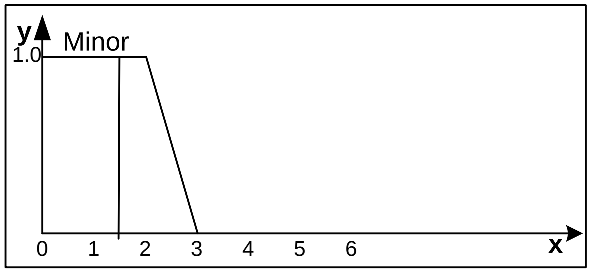

Fig. 6.9: MF-RL implication of R2

$$\mu_{B^2}(y) = 1.5000$$

<u>Step 3:</u> Substitute the values of α_2 and $\mu_{B^2}(y)$ *in Equation (6-3)*

Substituting α_2 and $\mu_{B^2}(y)$ in Equation (6-3) above will be expressed as below;

i.e. $\beta_2 = \min(0.1000, 1.5000)$

using fuzzy minimum operation on values 0.1000<1.500

then $\beta_2 = 0.1000$

Applying the same three steps approach, the implications for all the eight fired rules have been computed and the details are listed in Table 6.10 below;

Table 6.9 Fuzzy operation of implication of the fired rules

Rule No.	MF value of FLH	MF value of FCS	MF value of FCP	Firing strength
R2	0.9500	0.8000	0.1000	0.1000
R3	0.9500	0.2000	0.9000	0.2000
R7	0.0500	0.8000	0.9000	0.0500
R8	0.0500	0.2000	0.9000	0.0500
R27	0.9500	0.8000	0.1000	0.1000
R28	0.9500	0.2000	0.1000	0.2000
R32	0.0500	0.8000	0.1000	0.0500
R33	0.0500	0.2000	0.1000	0.0500

Stage 3: *Aggregation*

Aggregation is a process whereby the fuzzy sets of the outputs of each rule are combined into a single fuzzy set conducted once for each output variable. The membership functions of the truncated fuzzy set for each of the fired rules obtained after implication are further used as inputs for the aggregation process for each rule as illustrated in Figure 6.10. The output for the aggregation process is one fuzzy set for each of the output variable. Fuzzy maximum operation method is applied in the execution of this process as denoted below.

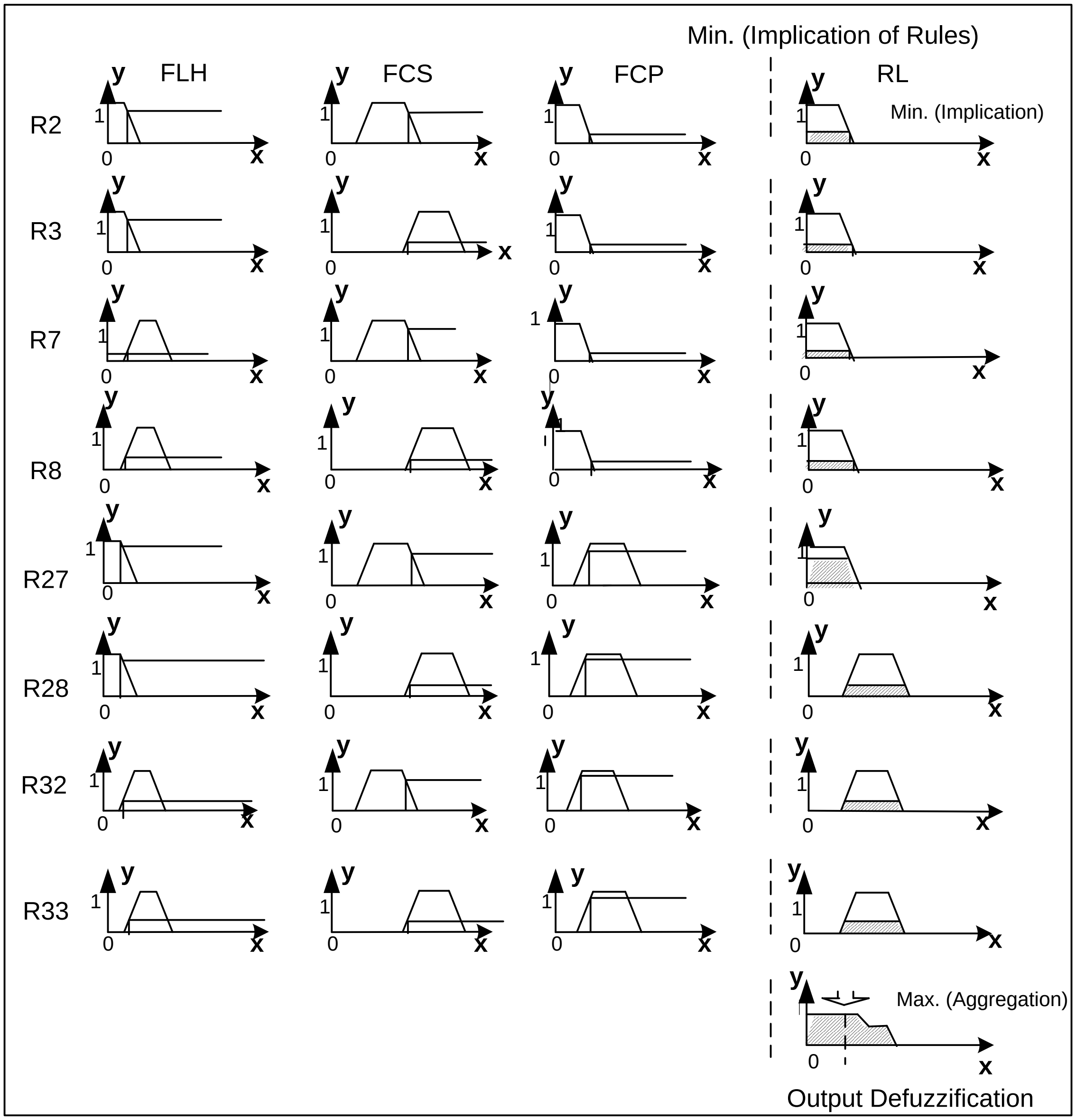

Fig.6.10: Implication process of the eight fired rules

This step combines all the eight outputs of implication processes into a single fuzzy set for which the membership function will be determined by the application of fuzzy maximum operators performed on the eight truncated membership functions in the output part and the value of this truncated membership function of the aggregated output is computed using Equation 6.4 below;

$$\mu_{agg}(y) = \max(\beta_2, \beta_3, \beta_7, \beta_8, \beta_{27}, \beta_{28}, \beta_{32}, \beta_{33}) \quad (6\text{-}4)$$

where $\mu_{agg}(y)$ is the MF value of output (risk level) after aggregation process.

6.2.4.6 Defuzzification

The aggregate output fuzzy set is used as input for the defuzzification process to obtain an output in a single number. Although fuzziness is required during the intermediate steps for the evaluation of the rule, the defuzzification is still necessary in order to determine a crisp value of the output.

$$y_{def} = \frac{\int_y y_1 \mu_{agg}(y)dy}{\int_y \mu_{agg}(y)dy} \qquad (6\text{-}5)$$

Even though the defuzzified single value is calculated using Equation (6-5) shown above, its discrete form is always used for simplicity. This discrete form is given in Equation (6-6) below and will thus be applied to compute to obtain the crisp value of the output as below:

$$y_{def} = \frac{\sum_{i=1}^{n} y_i \mu_{agg}(y_i)}{\sum_{i=1}^{n} \mu_{agg}(y_i)} \qquad (6\text{-}6)$$

$$y_{def} = \frac{(1.5\times0.10)+(1.5\times0.20)+(1.5\times0.05)+(1.5\times0.05)+(1.5\times0.10)+(4.0\times0.20)+(4.0\times0.05)+(4.0\times0.05)}{0.80+0.20+0.05+0.05+0.10+0.20+0.05+0.05}$$

$$y_{def} = 2.4375$$

According to the results of the aggregation as shown in Figure 6.11 and computed using as above, the defuzzified (crisp) value is obtained as shown in Figure 6.11.

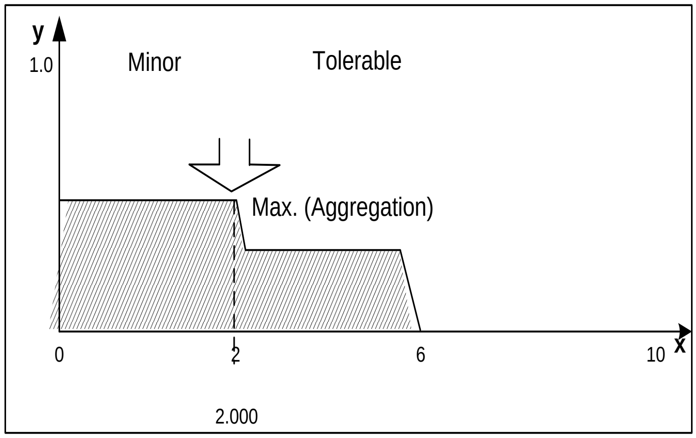

Fig.6.11: Aggregation of consequent output

The defuzzified output result of 2.4375 is applied in RL axis as shown in Figure. 6.12 below to determine the membership function of the RL and its corresponding value as shown in Figure 6.12. This clearly illustrates that, the RL value obtained belongs to *minor* and *tolerable* categories with a belief of 53% (MF=0.5282) and 47% (MF=0.4718) respectively. This result will thus provide safety analyst with useful information regarding the failure of the component used for the purpose of this demonstration. At this stage the risk information generated will enable safety analyst to make safety recommendations needed to modify and improve system design to make it safer.

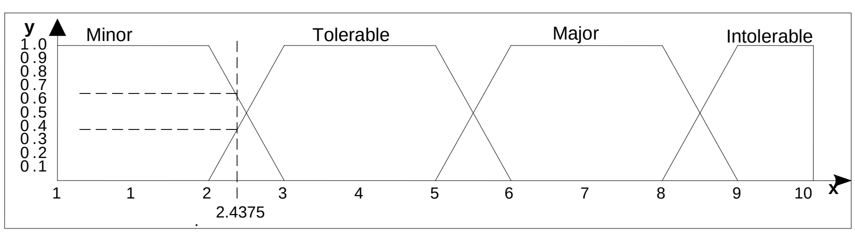

Fig.6.12: The result of risk level (RL) of the illustrated example

The outcomes of risk assessment using FRA at the component level as demonstrated in previous sections above where the levels of risks are expressed as the degrees of belonging to MFs of RL and illustrated in Figure 6.12. In this illustration the risk categories are defined with a belief of percentage for just one component failure event. Therefore to obtain the RLs at sub-system and the entire system levels fuzzy aggregation operation is applied progressively from component to sub-system level and finally to overall system level. For detailed demonstrations of how these are computed, the reader is referred to sections 7.3.4.6 & 7.3.4.7 in Chapter 7.

6.2.5 Risk response phase

The results produced from the risk estimation phase will provide the necessary information needed for the determination of appropriate responses to the associated risks. This information may also be used to assist risk analysts, design engineers, and managers in project design and, developing maintenance and operation policies. If risk is evaluated to be high, risk reduction measures must be applied or the system operation has to be reconsidered to reduce the occurrence probabilities or to control the possible consequences. On the other hand if risk is accepted to be negligible or inconsequential then, no further action would be required but the information produced needs to be recorded for certification purpose. However, it is important to note that the acceptable and unacceptable regions are usually divided by a transition region and any risk that falls within this transitional region must be reduced to ALARP (HSE, 1997). In this study, the RLs are categorised into four regions, i.e. ‘Minor’, ‘Tolerable’, ‘Major’ and ‘Intolerable’ These definitions are generally similar to those described by British, European and International Standards EN 50129, IEC 62278, BS EN ISO 12100-1, BS EN ISO 14121-1 and BS EN ISO 20815 (EN, 1998; IEC, 2008; ISO 2003, 2007 & 2008).

It is also important to note that risk assessment is not a one-off activity and therefore it becomes necessary for the safety needs to be reviewed at the appropriate intervals in order to update the risk assessment and provide risk information for appropriate responses. Detail responses to assessed risk will also be given in Chapter 7 using case study.

6.3 Summary

As referred severally in this report the data available from offshore platform installation is often saddled with high level of uncertainty, particularly, at early stage in design, which may necessitate the need for the use of subjective judgement, and vague data to conduct a risk analysis. The traditional quantified risk assessment methods such as fault tree analysis (FTA) and event tree analysis (ETA) may not effectively handle the vague risk data with high level of uncertainty in the recorded information. However, the fuzzy reasoning based method can offer a great potential in the risk assessment, especially in dealing with uncertainties. In contrast with the traditional methods mentioned earlier, the fuzzy logic reasoning approach has the following advantages (An *et al*, 2000a & 2007):

- It has the ability to integrate expert knowledge, engineering judgement, historical data and other risk analysis information to handle the safety and risk assessment in a more consistent manner;
- It can make use of ambiguous, imprecise, incomplete and uncertainty information in the assessment;
- The risk can simply be evaluated using the linguistic expressions which are employed in conducting risk assessment;
- It offers a more flexible structure for combining failure occurrence and consequence.

This chapter outlines the methodology of fuzzy reasoning approach in risk assessment of an offshore system. Illustrations have been used all through the procedure to demonstrate how the proposed risk analysis model can be used to progressively and effectively assess offshore platform design-based risks from component failure to sub-system level and finally to system level.

This chapter further describes how fuzzy reasoning approach is integrated and adopted to the concept of design for safety to develop a knowledge-based model for the assessment of risk of any chosen engineering system within the offshore domain. The effectiveness of the proposed model using real data collected from the industry will be detailed in Chapter 7. The results of case study will be used to demonstrate the ability of the proposed model to effectively assess the offshore platform risks in order to compliment the various techniques currently being used within the industry and to facilitate decision-making process.

CHAPTER 7

Case Study

7.1 Background

This Chapter describes the work carried out for testing the performance of the proposed knowledge-based risk assessment method (KBRAM), and the preliminary validation studies. The Chapter begins with the demonstration of how the method is used to process safety information by the application of the failure data collected from the industry. In this case the data is for the offshore processing unit of an offshore oil and gas platform. The KBRAM is applied to ensure that, the safety requirements are adequately integrated in the design of complex engineering systems such as offshore oil and gas platform.

It is pertinent to note that, the operation of the processing unit is probably the most hazardous activity related to the transportation and drilling operation on an offshore oil and gas platform. Past experiences of onshore and offshore oil and gas activities have revealed that a small miss-happening in the process operation might escalate to a catastrophe, which is of special concern in the offshore oil and gas platform especially due to the limited space and compact geometry of the process area coupled with limited ventilation and difficult escape routes. It is important to note that each extra controls measure added on the offshore oil and gas platform do not only occupy space but also increase congestion and add extra load to the platform.

However, eventualities in the offshore oil and gas platform process operation can be minimised by incorporating appropriate control measures at the early design stage. The proposed risk assessment methodology is applied to various sub-systems of the offshore process unit referred to in this report as the overall system. These sub-systems include the separators (Oil & Condensate), compressors 1 & 2, flash drum and driers for which appropriate safety measures are recommended based on their individually identified risk potentials.

This Chapter also illustrates how adoption of the concept of the design for safety measures can contribute positively towards controlling risks to a more acceptable level.

7.2 Description of an Offshore Processing Unit (OPU)

The main function of the offshore production platform is to operate the wells, and to separate the fluid from the wells into oil, gas-condensate, gas and water. It subsequently pumps oil, gas-condensate and gas to the onshore facilities. The offshore platform processing plant has three main parts, i.e. the wellhead, the separators and the gas compression. The layout of the process plant is shown in Figure 7.1.

Production lines from individual wells terminate at the wellhead, and each line being topped by a ‘Christmas tree.’ The well fluid passes through a manifold and is withdrawn at a production separator through a wing valve. The main hazard from the well is blowout which is likely to occur during work-over of the well. However, the present case study does not cover wellhead system hazards but focuses mainly on the major separation and compression parts of the process system.

The fluid from the well is then conveyed through separators where it is separated into the four major products as mentioned above. Oil is pumped through the main oil line to the onshore facilities and part of the condensate is pumped along with the oil. Gas compression is achieved using centrifugal compressors before it is subsequently delivered through the flash drum where the temperature is reduced and then condensate formed and separated out.

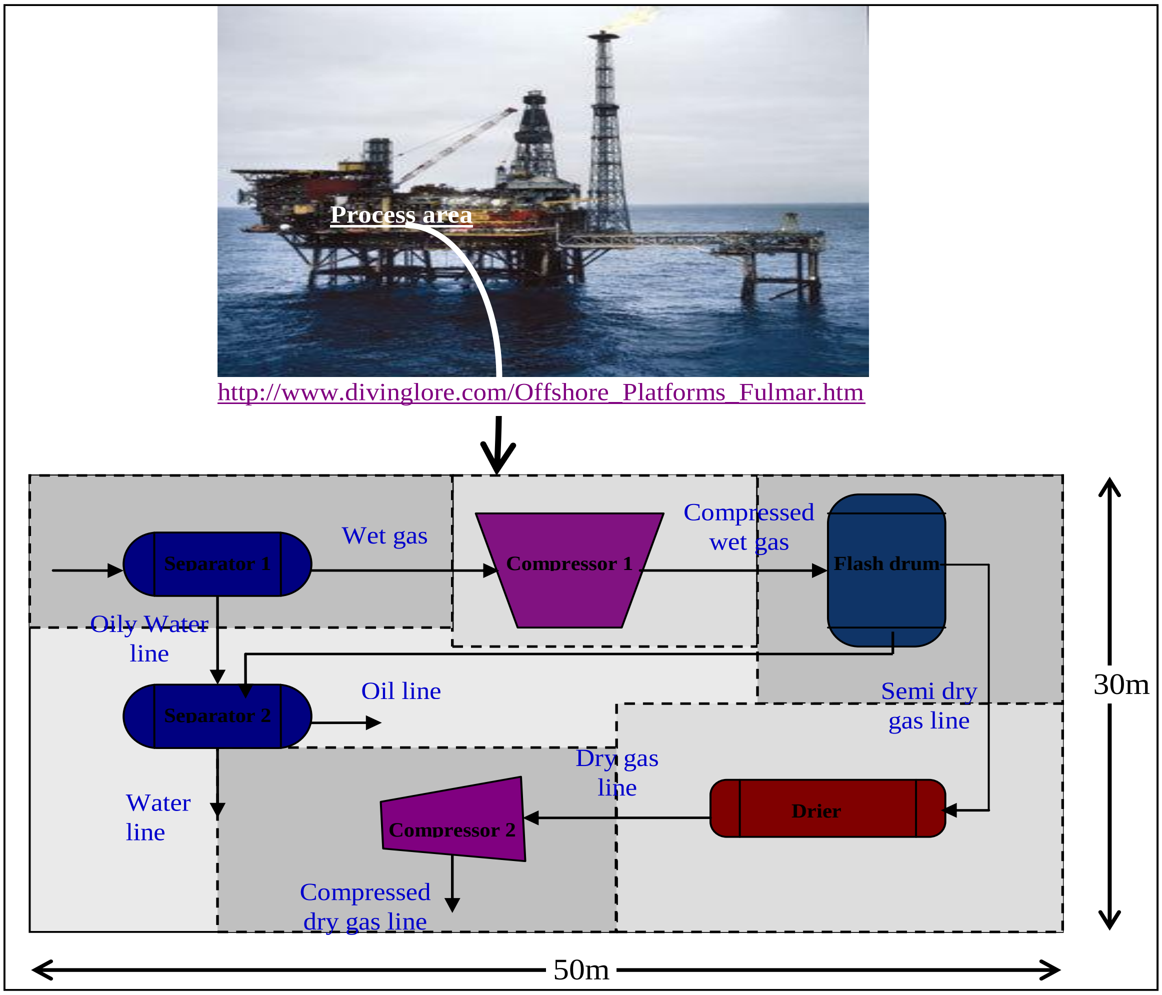

Fig. 7.1: Offshore platform process plant layout

The gas is then dried and purified before it is further compressed to high-pressure through reciprocating compressors. Part of the gas is used at the wells for power generation on the platform while the remaining gas is pumped to the onshore facilities leaving a small amount to be flared. A simplified process flow diagram is presented in Figure 7.2 in order to present clearer details on the configuration of offshore platform.

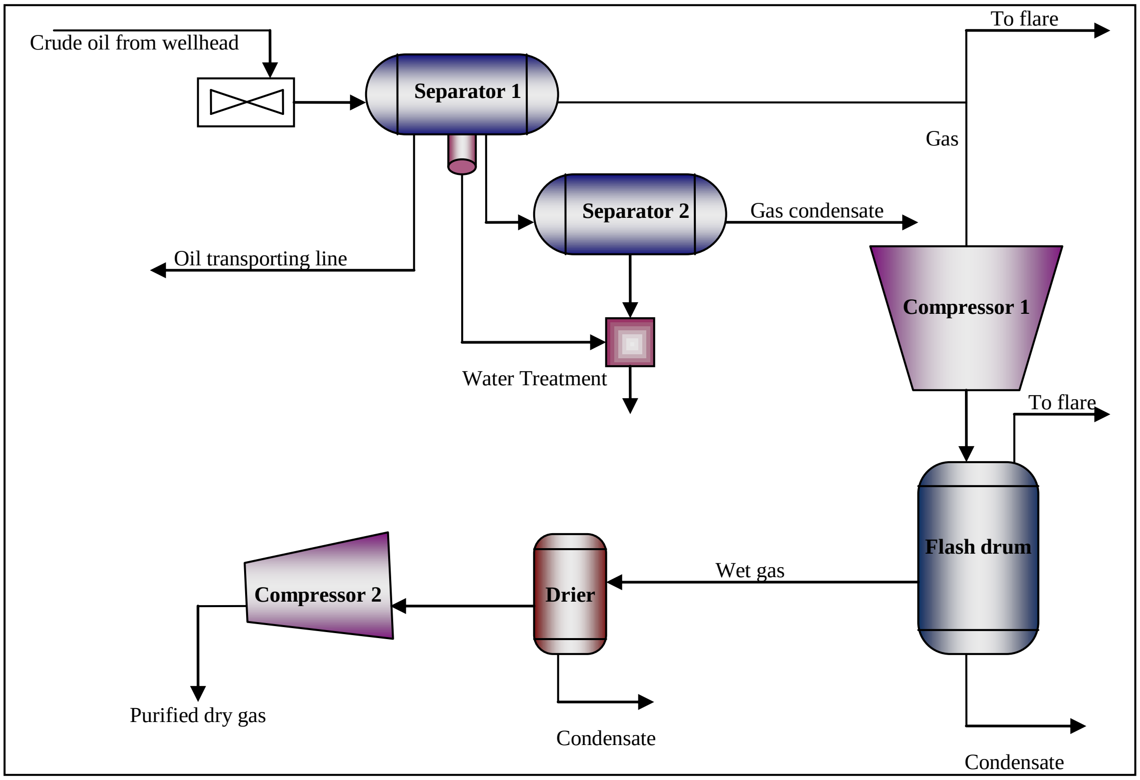

Fig.7.2: A simplified process flow diagram

7.3 Offshore Processing Unit Risk Assessment using KBRAM

A case study of risk assessment on offshore platform processing unit is presented to demonstrate the application of the proposed risk assessment method developed for the achievement of safer designed sub-system. This safe design concept is intended to facilitate decision-making through safety cost evaluations derived from the results obtained through the application of KBRAM.

Figure 7.2 shows the processing unit consisting of six sub-systems: oil separator (SP1), condensate separator (SP2), compressors (CP1 & 2), flash drum (FD), and drier (DR) which will be used to demonstrate the KBRAM in the following sections.

7.3.1 Data Collection and Analysis for Offshore Processing Unit

The complete process system comprising separators, compressors, and pipelines has been studied in details. Safety measures are designed and implemented on each of the six process sub-systems based on the hazard identification studies presented by Khan *et al*, (2002b). The results from industry records, personnel interviews and previous hazard studies indicated that separators, compressors, drier and flash drum are considered as highly hazardous sub-systems, whereas the pipelines and pumps are considered to be moderately hazardous sub-systems. A detailed study on failures related to both the highly hazardous and moderately hazardous sub-systems is presented to illustrate and validate the efficiency of the proposed knowledge-based risk assessment method with reference to the results obtained as demonstrated in the following sections.

7.3.2 Risk Identification for Offshore Processing Unit

The Historical data of accidents and incidents recorded over the past period of time are assembled to generate the necessary input for the conduct of a risk assessment. This failure data has been reviewed identified and grouped into the six vital hazard groups as presented by Khan, *et al*, (2002b). Accordingly, each hazard group was further examined to identify a number of hazardous events which have also been verified by the risk assessments team listed in Table 7.1.

7.3.2.1 Establishment of risk assessment team

As explained in Chapter 6, in conducting this case study six experts with high knowledge of safety requirements on the offshore processing system have been carefully assembled to constitute a risk assessment team vested with the responsibility of conducting the risk assessment using the proposed knowledge-based risk assessment method. As mentioned in Chapter 6, experts' weighted factors (WFs) have been assigned to each member based on their individual knowledge and experience.

Table 7.1 below give the list of experts working with one of the world leading major oil & gas producing company. This list comprises of employees of the above company stationed in both West Africa and Middle East and referred to in this report as Nivi & Team for confidential reasons.

As discussed in section 6.2.3.1 and further explained in section 6.2.4.4 experts contribution factors must sum up to 1 $\left(\sum_{i=1}^{n} w_i = 1\right)$ and are assigned based on expertise, skills, status and experiences, thus Nivi & Team contribution factors are as shown in Table 7.1 below;

Table 7.1 Risk assessment team and Contribution factors

Expert	Position	Years of	Contribution Factor Determinants			Assigned
		Experience	Expertise	Status	Experience	Contribution Factor
E1	Safety Officer	<5 Yrs	15	10	5	0.3
E2	Safety Advisor	>5 Yrs	10	5	5	0.2
E3	Operations Superintendent	<5 Yrs	10	5	5	0.2
E4	Maintenance Supervisor	<5 Yrs	3	2	5	0.1
E5	Operations Engineer	>5 Yrs	3	2	5	0.1
E6	Operations Engineer	>5 Yrs	3	2	5	0.1

The contribution factors are obtained by scoring a maximum point of 100 spread the three main factors with per expert with pro-rated points of between 0 and 15 to arrive at the assigned contribution factors.

Each member of the risk management team expressed their individual assessment through responses to questionnaires and interviews, on the levels of consequence severity and consequence probability of the identified top events based on component failures using the failure data collated from the industry for the process unit. These expert assessments have been harmonised with the data on the inherent risk with reference to fire and explosion which are considered to be the most challenging to the operations of offshore platform processing unit. These inherent risks have been assessed carefully for the purposes of mitigation and decision making through design. The experts agreed that the data collected has adequate information regarding the top events and their corresponding failure frequencies and/or likelihood for all the critical components for the various sub-units (sub-system) of the processing unit (system). The team therefore, concentrated on the task of risk assessment using this information to measure the levels of severity of consequences and the probability of consequence resulting from each component failure which is applied to both sub-system and system levels. This proposed method is intended to compliment the efforts of various existing methods with particular reference to dealing with subjectivities and uncertainties associated with the data in order to demonstrate some measure of relative enhanced effectiveness.

Following discussions with relevant managers and operators of shell OMAN and NIGERIA the list of identified risks associated with OPU has been compiled and verified to contain all possible failures, the result of which is now reflected in table 7.2 below (Nivi & Team, 2007);

Table 7.2 Offshore processing unit hazardous events (Nivi & Team, 2007)

Sub-System	Component Failure Mode	Failure Code
Separator 1	Flow control valve	S1-1
	Leak indicator failed	S1-2
	Excess flow at upstream	S1-3
	Impurities causing exothermic reaction	S1-4
	Sudden change in pressure	S1-5
	Temperature controller failed	S1-6
	High pressure upstream line	S1-7
	Upstream pressure controller failed	S1-8
	Condensate line choked	S1-9
	Oil pipeline or valve choked	S1-10
	Gas pipeline or valve choke	S1-11
	Safety valve undersize	S1-12
	Safety/pressure valve choked or not function on demand	S1-13
	External heating	S1-14
	Exothermic reaction in vessel	S1-15
	Temperature controller failed	S1-16
	Pressure controller system of separator failed	S1-17
	Pressure or safety release failed	S1-18
	Ignition due to explosion energy	S1-19
	Ignition due to heat from surrounding	S1-20
	Electric spark as source of ignition	S1-21
Separator 2	Leak from joints	S2-1
	Leak from main pipeline	S2-2
	Leak from joints	S2-3
	Leak from main pipeline	S2-4
	Leak from vessel	S2-5
	Leak from fracture, joints or crack	S2-6
	Leak from the pipe connection	S2-7
	Leak from safety valve	S2-8
	Leak from pressure release valve	S2-9
	Leak from control valves	S2-10
	Outlet pipe choked	S2-11
	High pressure upstream line	S2-12
	Sudden phase change	S2-13
	External heat absorption causing increase in pressure	S2-14
	Ignition due to explosion energy	S2-15
	Ignition due to external heat from surrounding	S2-16
	Ignition due to electric spark	S2-17
	Release from pipe after explosion	S2-18
	Release from vessel aftermath of explosion	S2-19
	Ignition due to external explosion energy	S2-20
	Ignition due to fire heat load	S2-21

Table 7.2 Continue (Nivi & Team, 2007)

Sub-System	Component Failure Mode	Failure Code
Compressors	Leak from compressor downstream pipeline	CP-1
	Leak from compressor downstream pipeline joints	CP-2
	Leak from compressor upstream pipeline	CP-3
	Leak from joints of compressor upstream pipeline	CP-4
	Release from casing of compressor	CP-5
	Leaking of seal	CP-6
	Release from impeller	CP-7
	Compressor completely failed causing release of chemical	CP-8
	Leak from junction of pump and pipeline	CP-9
	Leak from rotor	CP-10
	Pump failed to operate and caused release of chemical	CP-11
	Leak from casing	CP-12
	Ignition due to explosion energy	CP-13
	Ignition due to external heat from surrounding	CP-14
	Ignition due to electric spark	CP-15
	Fire caused by failure of pipeline	CP-16
	Fire caused vessel to fail & release of chemical	CP-17
Flush Drum	Leak from upstream pipeline	FD-1
	Leak from upstream pipeline joints	FD-2
	High-pressure in vessel causing rupture & release of gas	FD-3
	Leak from joints or flange	FD-4
	Leak from downstream pipeline	FD-5
	Leak from joints of downstream pipeline	FD-6
	Leak from joint of gas pipeline	FD-7
	Leak from gas pipeline	FD-8
	Ignition due to explosion energy	FD-9
	Ignition due to external heat from surrounding	FD-10
	Ignition due to electric spark	FD-11
	Ignition due to explosion energy	FD-12
	Ignition due to external heat from surrounding	FD-13
	VCE causes pipeline to fail and release chemical	FD-14
	VCE causes vessel to fail and release chemical	FD-15
Drier	Impurities in feed line	DR-1
	Control system failed	DR-2
	Sudden phase change	DR-3
	Temperature controller failed	DR-4
	Heating due to external heat source	DR-5
	Drier outlet line choked	DR-6
	Outlet valve choked	DR-7
	Safety valve failed to operate on demand	DR-8
	Pressure relief failed to operate on demand	DR-9
	Ignition due to external heat from surroundings	DR-10
	Ignition due to electric spark	DR-11
	Ignition due to explosion energy	DR-12
	Ignition due to external heat from surroundings	DR-13
	BLEVE causes vessel to fail and release chemical	DR-14
	BLEVE causes pipeline to fail and release chemical	DR-15

Questionnaire was designed and discussed with Nivi & Team, (2007) based on the listed failure event in Table 7.2. Quality check of the questionnaire was conducted by the author’s supervisors to ensure all the necessary informations regarding the chosen installations are adequately captured for effective analysis and achievement of reliable results.

1. ***SP1 (Oil separator)****:* - The cumulative effect of overpressure and heat load may result in the release of a chemical gas from other units, which on ignition would cause a fire. This type of failure has high possibility of causing fatality as well as trigger accidents in other units such as condensate separator, the oil transportation pipeline, and the main pumping station.

*Damage potential estimation***: -** The result for separator 1 failures is *boiling liquid expanding vapour explosion* (*BLEVE)* to be followed by fire. BLEVE would generate fatal overpressure over an area and the vapour cloud generated by the released chemical on ignition causes a fireball, which would generate a heat radiation effect. This type of failure has high possibility of causing fatality due to heat load. The overpressure and heat radiation effect may cause a fatality as well as second-tier accidents through damages to other units such as separator 2, the oil transportation pipeline, and the main pumping station.

2. ***SP2 (Condensate separator):*** - The failure involves release of chemical forming vapour cloud which on ignition would cause *vapor cloud explosion* (*VCE*) and eventual fire capable causing severe damage to the condensate and gas pipelines.

*Damage potential estimation***: -** VCE followed by fire would cause considerable damage. There is high possibility that damage could have high level of consequence severity due to a combination of overpressure and shockwave.

The residue or left over chemical within the unit would burn as a pool fire resulting in possible combination of heat load and shockwave. This possible combination unit could initiate secondary and a higher order of accidents in the neighbouring units such as condensate and gas pipeline.

3. ***CP (Compressors 1 & 2):*** - the continuous release of flammable gas from compressor 1 on ignition would cause a jet fire, which may generate the lethal heat load resulting in possible fatality and damage. Flash drum and the drier are likely to be affected by this failure.

*Damage potential estimation**:** -*: Compressor I: It is evident from that this scenario would cause moderate damage. There is no likelihood of overpressure development, however, a fire jet may result and generate lethal heat load with the potential of causing fatality and damage. There is also a possibility that the jet flame may trigger some damages in the units within its close proximity either through direct impact or by external heat load. The units likely to be affected by this accident are the flash drum and the drier.

*Damage potential estimation**:*** Compressor 2: It is evident from that this scenario would cause moderate damage. There is no likelihood of overpressure development, however, a fire jet may result and generate lethal heat load with the potential of causing fatality and damage. There is also a possibility that the jet flame may trigger some damages in the units within its close proximity either through direct impact or by external heat load. The units likely to be affected by this accident are the drier and the pipeline.

4. ***FD (Flash drum)***: - The failure involves the release of gas which on ignition would cause a fireball while the cumulative effect of overpressure and heat may cause other units to fail and result in pool and/or jet fires. The burning of a vapor cloud as well as a liquid pool would generate a lethal heat load which would cover a larger area. This sub-unit does not pose any serious threat.

Damage potential estimation: The flash drum poses lesser hazards compared to the separators. It is evident that damage causing shockwaves would be effective only to a limited area. The burning of a vapor cloud as well as a liquid pool would generate a lethal heat load which would cover a larger area. As evident from the detailed descriptions of the failure scenario, this unit does not pose a serious threat and there is less likely to result in secondary accident.

5. *DR (Drier*): - The drier is another important unit in the process facility as it handles a large quantity of flammable gas at high-pressure. The released chemical on ignition would cause a fireball and a pool fire generated heat load has capabilities of causing fatality and damage over a wider area. The sub-units likely to be affected are compressors and gas transportation line.

Damage potential estimation: Drier; Lethal overpressure load is enough to cause fatality, and damage would cover a reasonable area. The released chemical on ignition would cause a fireball and a pool fire due to leftover chemical in the unit. This lethal heat load has capabilities of causing fatality and damage which could extend to a wider area. It is also likely that overpressure and heat radiation load may cause other units to fail as secondary accidents.

7.3.3 Risk Estimation for Offshore Processing Unit

This is the stage where input parameters are measured, fuzzified, aggregated and defuzzified using Equations (6-1) to (6-6) to obtain crisp values in order to accurately define output implication. These values are further applied to the output membership function (MF) to express risk level (RL) as degree of percentage of belonging to any or a combination of two linguistic risk categories. The risk estimation steps are explained in the subsequent sections.

7.3.3.1 Establishment of risk parameters

In this case study the failure likelihood (FLH) has been adopted from the industry data for the identified top events at the component level. Therefore, the task is the measurement of failure consequence severity (FCS) and failure consequence probability (FCP), which involves steps, like measurement of FCS and FCP by the experts, conversion of individual assessment by applying experts' weighted factors (WF) as given in Table 7.1 and aggregation of the scores into expert collective assessment for each component failure event by substituting corresponding value in Equation 6.1.

The input parameters are FLH, FCS and FCP of failure events and the outputs of risk assessment are RLs of failure events, at component level, sub-system level and the overall system of the offshore processing unit with risk scores located from 0 to 10. These scores will then be applied through the modeling procedures to obtain corresponding risk levels (RLs) belonging to category or categories as '*Minor', 'Tolerable', 'Major'* and *'Intolerable'* expressed in percentage belief. The RLs for all the sub-systems are calculated using the principles of fuzzy reasoning approach (FRA) based on the aggregation of the results for each failure event belonging to the particular subsystems.

The overall RL for the system is obtained based on the aggregated implication of all the fired rules from all the constituent components of the various sub-systems as listed in Table 7.1.

7.3.3.2 Establishment fuzzy membership functions (MFs) for the risk parameters

As mentioned earlier in this report, the three input parameters of FLH, FCS and FCP, are selected for assessing the RL of the identified top events of the offshore platform processing unit from components through sub- system to overall system levels. The six experts have also agreed with five linguistic terms to describe the three input parameters i.e. FLH as *very low* (VL), *low* (Lo), *average* (Av), *high* (Hh) and *very high* (VH), for FCS as *negligible* (Ne), *marginal* (Mg), *moderate* (Md), *severe* (Se) and *catastrophic* (Ct), and FCP as *highly-unlikely* (HU), *unlikely* *(*Ul), *likely* (Li), *highly-likely* (HL) and *definite* (Df). However, for the output parameter RL, they agreed to use four linguistic terms described as *minor* (Mn), *tolerable* (To), *major* (Mj) and *intolerable* (It).

The risk descriptions of FLH, FCS, FCP, and RL are shown in Tables 6.1, 6.2, 6.3 & 6.4, which are defined by Trapezoidal MFs as shown in Figures 6.2, 6.3, 6.4 & 6.5.

7.3.3.3 Fuzzification using case study example

This process as described earlier will in this proposed offshore risk assessment be applied to convert input parameters FLH, FCS and FCP into their fuzzy qualitative descriptors of Z_{FLH}, Z_{FCS} and Z_{FCP} respectively in order to determine the degree of belonging of each of the appropriate fuzzy set in rule base via MF assumptions of FLH and computations of weighted scores for FCS are as demonstrated in the following sections;

In determining the fired rules using case study, for example the failure of safety and/or pressure valve chocking or failure on demand in Separator 1 coded SP1-13 was considered and mapped as shown in Figure 7.3. These values indicate that, this component failure has likelihood (FLH) of 0.002 events per year and the corresponding values (scores) of 3.92 and 3.04, for FCS and FCP respectively as obtained using Equation (6-1) as expressed in chapter 6 to compute experts' weighted scores.

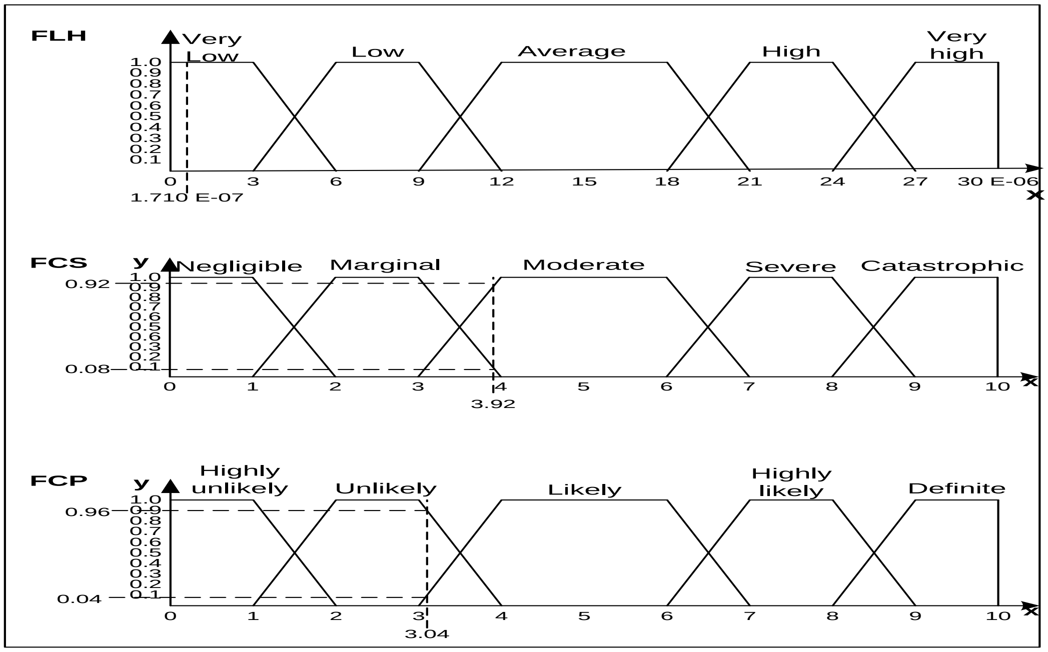

Fig.7.3: MFs of three input parameters for SP1-13

These input values are further used to determine the linguistic classifications and MFs for each of the three input parameters which are summarised in Table 7.3 below.

Table 7.3 SP1-13 Fuzzification

Input Parameter	Input Value	Linguistic Class	Membership Function
FLH	1.71E-07	Very low	1.00
FCS	3.92	Marginal	0.08
		Moderate	0.92
FCP	3.04	Unlikely	0.04
		Likely	0.96

7.3.3.4 Application of fuzzy inference engine process using case study example

Applying the fuzzy inference engine procedure as demonstrated in Section 6.2.4.5 of Chapter 6, the input details in Table 7.3 above have been combined in the fuzzy rule base to determine the fired rules. These established fired rules are further required through the processes of fuzzy inference engine in order to establish the risk implications as demonstrated.

Stage 1: *Evaluation of fuzzy rules*

The conclusion of the fuzzy rules evaluation as described in Chapter 6, in this case turned out four fired rules from the rule base as the four rules turn out non-zero values, and these are listed in Table 7.4.

Table 7.4 Fired rules for SP1-13

Rule No.	Rule Description
R27	IF FLH is Very low and FCS is Marginal and FCP is Unlikely THEN RL is Minor
R28	IF FLH is Very low and FCS is Moderate and FCP is Unlikely THEN RL is Tolerable
R52	IF FLH is Very low and FCS is Marginal and FCP is Unlikely THEN RL is Tolerable
R53	IF FLH is Very low and FCS is Moderate and FCP is Unlikely THEN RL is Tolerable

The four fired rules will therefore be processed further through the application of fuzzy minimum operator and Equation (6-2) as in Chapter 6 to compute the rules respective firing strengths and the result is as shown in Table 7.5.

Table 7.5 SP1-13 Fired rules fuzzy operations

Rule No.	MF value of FLH	MF value of FCS	MF value of FCP	Firing Strength
R27	1.00	0.08	0.96	0.08
R28	1.00	0.92	0.96	0.92
R52	1.00	0.08	0.04	0.04
R53	1.00	0.92	0.04	0.04

Stage 2: *Implication*

The implication from antecedent to consequent can be obtained by fuzzy minimum operator method based on the firing strength of each rule. The implication output is obtained also through the application of fuzzy minimum operator and Equation (6-3) to compute their corresponding implications as described in Chapter 6 and the result is summarised in Table 7.6.

Table 7.6 SP1-13 Fired rules implication

Rule No.	Firing Strength	MF Value of RL	MF Value of Implication
R27	0.08	1.50	0.08
R28	0.92	4.00	0.92
R52	0.04	4.00	0.04
R53	0.04	4.00	0.04

Stage 3: *Aggregation*

The output for the aggregation process is one fuzzy set for each of the output variable. Fuzzy maximum operation method is applied in the execution of this process to obtain results as shown in Figure 7.4 below.

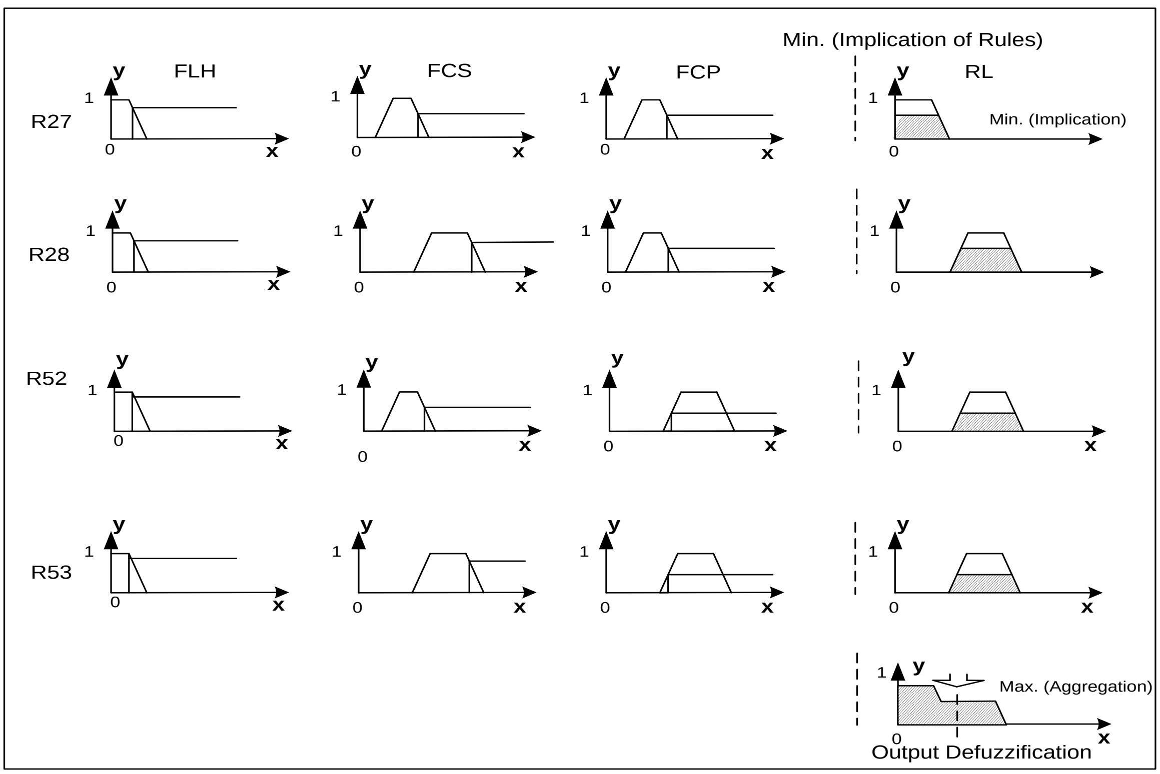

Fig.7.4: Implication process of the four fired rules

This step combines all the four outputs of implication processes into a single fuzzy set for which the membership function is determined by the application of fuzzy maximum operators performed on the four truncated membership functions and the value of this truncated membership function of the aggregated output is computed using Equation (6-4) as described and demonstrated in Chapter 6.

7.3.3.5 Defuzzification

As demonstrated in Chapter 6, the aggregate output fuzzy set is used as input for the defuzzification process to obtain an output in a single number. Equation (6-6) is applied to compute and obtain the crisp value of the output as below:

$$y_{def} = \frac{(1.5\times0.08)+(4.0\times0.92)+(4.0\times0.04)+(4.0\times0.04)}{0.08+0.92+0.04+0.04}$$

$$y_{def} = 3.8148$$

According to the aggregation result shown in Fig 7.4 and computed using Equation (6-6) as above, the defuzzified or crisp value of 3.8148 is obtained and the process expressed in Figure 7.5 below;

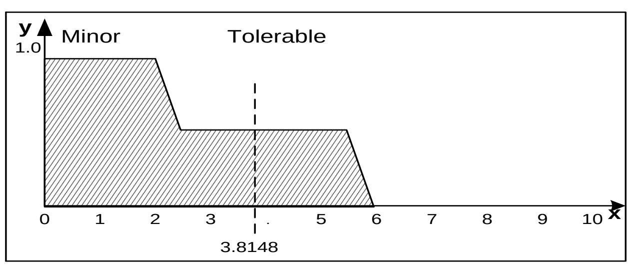

Fig.7.5: Aggregation of consequent output

This defuzzified output value of 3.8148 as shown above is applied in RL axis as shown in Figure. 7.6 to determine the membership function of the risk level and its corresponding value. The illustrations in Figure 7.6 shows that the RL value belongs to *tolerable* category with belief of 100% (MF=1.00) respectively. This procedure was applied to all the failures events from component level to sub-system level and finally the overall system level i.e. offshore processing unit.

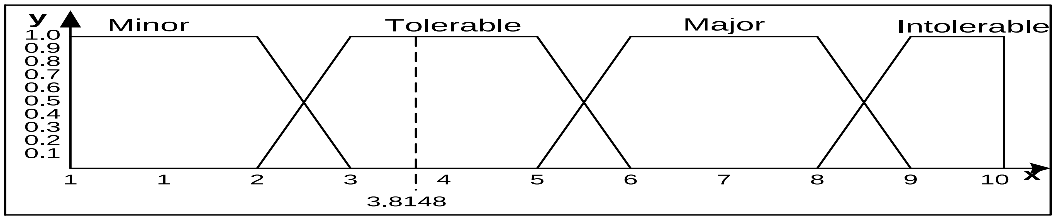

Fig.7.6: The result of risk level (RL) of the illustrated example

The outcomes of risk assessment using FRA at the component level as demonstrated in previous sections above where the level of risks are expressed also as the degrees of belonging to membership functions (MFs) of risk level (RL) for SP1-13 and illustrated in Figure 7.12, and the results are summarised in Table 7.7.

Therefore to obtain the RLs at sub-system and the entire system levels fuzzy aggregation operation is applied progressively to sub-system levels and eventually overall system level as will be demonstrated and discussed in the subsequent sections of this Chapter.

The result of the above process will be expressed in one or a maximum combination of two out of the four linguistic categories for the risk level this information is used to draw conclusion and make recommendations needed to facilitate the decision making process. For example, if the risk belongs to either tolerable or minor category or a combination of both then the control measures may be based on economic cost benefit analysis. However, for risk belonging to either major and/or intolerable design review would be recommended in order to re-assess the risk and apply necessary measures to reduce the risk to ALARP level.

According to the above, the safety analyst will make safety recommendations including risk responses needed to modify and improve the component quality through design to make it safer and more reliable.

7.3.4 Internal Validation of Experts Jugdements

7.3.4.1 Typical Expert Scores

Table 7.7 below shows the result of internal validation of a typical expert scores extracted from the raw data reflecting their responses to the questionnaire. These scores are specifically for the failure event coded S1-12 in Table 7.2 related to undersize safety valve fitted to an offshore processing unit (OPU).

Table 7.7 Validation of Experts Judgements

		Expert 1			Expert 2			Expert 3			Expert 4			Expert 5			Expert 6		
Parameter	Failure Frequency	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function
FLH	5.92E-05		Very low	0.10		Very low	0.10		Very low	0.10		Very low	0.10		Very low	0.10		Very low	0.10
			Low	0.90		Low	0.90		Low	0.90		Low	0.90		Low	0.90		Low	0.90
FCS		4.5	Moderate	1.00	4.0	Moderate	1.00	3.0	Marginal	1.00	6.5	Moderate	0.50	4.0	Marginal	0.50	6.5	Moderate	0.50
						-	-					Severe	0.50		Moderate	0.50		Severe	0.50
FCP		5.0	Likely	1.00	2.5	Unlikely	1.00	3.5	Unlikely	0.50	5.0	likely	1.00	2.5	likely	1.00	5.0	likely	1.00
									Likely	0.50									
Risk Score		4.00			4.00			3.79			5.25				4.80		5.25		
Risk Level		Tolerable		100%	Tolerable		100%	Tolerable		100%	Tolerable		71%	Tolerable		100%	Tolerable		71%
		-		-	-		-	-		-	Major		29%	-		-	Major		29%

Figure 7.7 below further shows that internal validation of experts judgement indicating data consistency when applies to the model as all the five experts posted risk level substantially within the tolerable region with on. This result confirms the consistency of fuzzy knowledge-based method (KBRAM) thus deomstarting the reliability of the model.

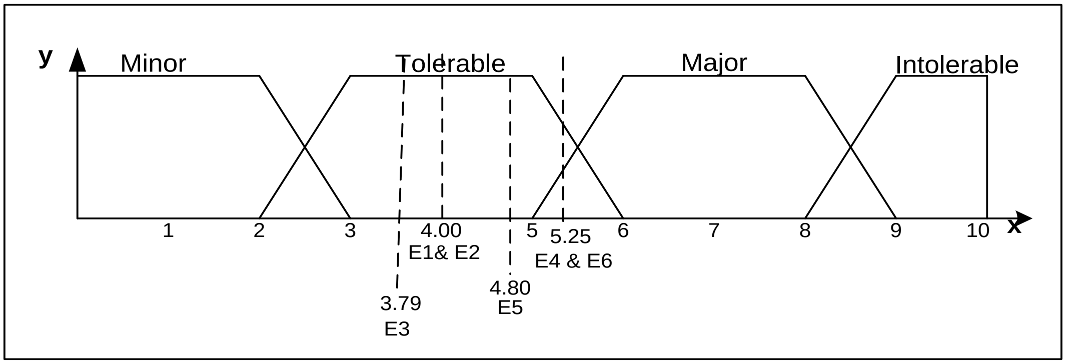

Fig.7.7: The result of risk level (RL) of the illustrated example for typical scores

7.3.4.2 Most Disperse Expert Scores

Table 7.8 below shows the result of internal validation of a typical expert scores extracted from the raw data reflecting their responses to the questionnaire. These scores are specifically for the failure event coded S1-1 in Table 7.2 related to flow control valve fitted to an offshore processing unit (OPU).

Table 7.8 Validation of Experts Disperse Scores

		Expert 1			Expert 2			Expert 3			Expert 4			Expert 5			Expert 6		
Parameter	Failure Frequency	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function	Expert Score	Linguistic Class	Membership Function
FLH	2.85E-06	Very low		0.30	Very low		0.30	Very low		0.30	Very low		0.30	Very low		0.30		Very low	0.30
		Low		0.70	Low		0.70	Low		0.70	Low		0.70	Low		0.70		Low	0.70
FCS		8.0	Severe	1.00	10.0	Severe	1.00	4.0	Moderate	1.00	5.0	Moderate	1.00	4.0	Moderate	1.00	7.0	Severe	1.00
			-	-		-	-		-	-		-	-		-	-			
FCP		4.0	Likely	1.00	4.0	Likely	1.00	6.0	Likely	1.00	6.0	Likely	1.00	4.0	Likely	1.00	5.0	Likely	1.00
			-	-					-	-		-	-		-	-			
Risk Score		6.10			6.10			4.00			4.00			4.00			6.10		
Risk Level		Major		100%	Major		100%	Tolerable		100%	Tolerable		100%	Tolerable		100%	Major		100%
		-		-	-		-	-		-	-		-	-		-	-		-

Figure 7.8 below furher shows that internal validation of disperse experts score indicating data consistency when applies to the model as all the five experts posted risk level substantially within

the tolerable region with on. This result confirms the consistency of fuzzy knowledge-based method (KBRAM) thus deomstarting the reliability of the model.

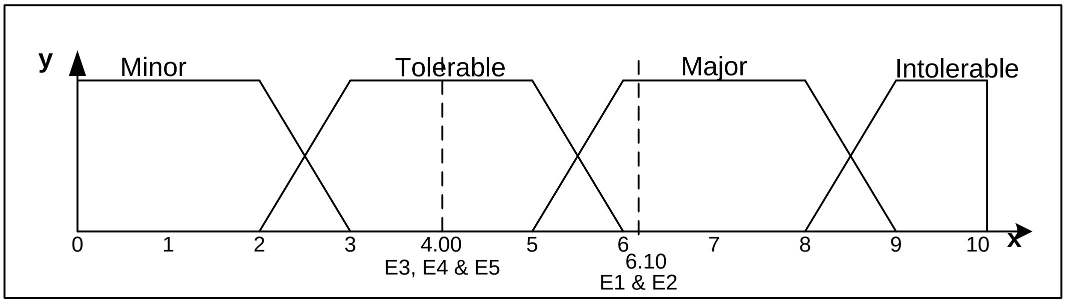

Fig.7.8: The result of risk level (RL) of the illustrated example for disperse scores

Table 7.9 Membership Functions of OPU component failures

Component Failure Code	Failure Likelihood						Failure Consequence Severity						Failure Consequence Probability					
	Value E-06	Very Low	Low	Average	High	Very High	Weighted Score	Negligible	Marginal	Moderate	Severe	Catastrophic	Weighted Score	Highly Unlikely	Unlikely	Likely	Highly Likely	Definite
S1-1	2.85E-06	1.00	0	0	0	0	3.04	0	0.96	0.04	0	0	2.24	0	1.00	0	0	0
S1-2	2.28E-06	1.00	0	0	0	0	2.96	0	1.00	0	0	0	2.24	0	1.00	0	0	0
S1-3	9.11E-06	0	1.00		0	0	2.80	0	1.00	0	0	0	2.48	0	1.00	0	0	0
S1-4	3.42E-07	1.00		0	0	0	3.28	0	0.28	0.72	0	0	1.84	0.16	0.84	0	0	0
S1-5	1.94E-06	1.00	0	0.00	0	0	2.80	0	1.00	0	0	0	2.56	0	1.00	0	0	0
S1-6	2.28E-06	1.00	0	0	0	0	3.04	0	0.96	0.04	0	0	2.56	0	1.00	0	0	0
S1-7	7.97E-06	0	1.00	0	0	0	2.88	0	1.00	0	0	0	2.56	0	1.00	0	0	0
S1-8	2.85E-06	0.30	0.70	0	0	0	3.04	0	0.96	0.04	0	0	2.40	0	1.00	0	0	0
S1-9	2.39E-07	1.00	0	0	0	0	2.64	0	1.00	0	0	0	2.64	0	1.00	0	0	0
S1-10	8.54E-07	1.00	0	0	0	0	3.04	0	0.96	0.04	0	0	2.64	0	1.00	0	0	0
S1-11	1.71E-07	1.00	0	0	0	0	3.04	0	0.96	0.04	0	0	2.56	0	1.00	0	0	0
S1-12	5.69E-06	0.10	0.90	0	0	0	3.52	0	0.48	0.52	0	0	3.12	0	0.88	0.12	0	0
S1-13	1.71E-07	1.00	0	0	0	0	3.92	0	0.08	0.92	0	0	3.04	0	0.96	0.04	0	0
S1-14	1.71E-06	1.00	0	0	0	0	3.20	0	0.80	0.20	0	0	2.24	0	1.00	0	0	0
S1-15	3.42E-07	1.00	0	0	0	0	3.52	0	0.48	0.52	0	0	2.56	0	0	0	1.00	0
S1-16	2.28E-06	1.00	0	0	0	0	3.36	0	0.64	0.36	0	0	2.56	0	1.00	0	0	0
S1-17	2.28E-06	1.00	0	0	0	0	3.28	0	0.28	0.72	0	0	2.72	0	1.00	0	0	0
S1-18	1.71E-07	1.00	0	0	0	0	4.00	0	0	1.00	0	0	3.12	0	0.88	0.12	0	0
S1-19	1.71E-05	0	0	1.00	0	0	4.00	0	0	1.00	0	0	3.04	0	0.96	0.04	0	0
S1-20	2.28E-05	0	0	0	1.00	0	4.00	0	0	1.00	0	0	2.96	0	1.00	0	0	0
S1-21	2.85E-05	0	0	0	0	1.00	4.16	0	0	1.00	0	0	2.80	0	1.00	0	0	0
S2-1	5.12E-06	0.30	0.70	0	0	0	2.24	0	1.00	0	0	0	2.24	0	1.00	0	0	0
S2-2	3.42E-07	1.00	0	0	0	0	2.48	0	1.00	0	0	0	2.08	0	1.00	0	0	0
S2-3	5.12E-06	0.30	0.70	0	0	0	2.48	0	1.00	0	0	0	2.32	0	1.00	0	0	0
S2-4	3.42E-07	1.00	0	0	0	0	2.48	0	1.00	0	0	0	2.16	0	1.00	0	0	0
S2-5	1.71E-07	1.00	0	0	0	0	2.48	0	1.00	0	0	0	2.20	0	1.00	0	0	0
S2-6	4.55E-08	1.00	0	0	0	0	2.48	0	1.00	0	0	0	2.20	0	1.00	0	0	0
S2-7	7.40E-07	1.00	0	0	0	0	2.64	0	1.00	0	0	0	2.36	0	1.00	0	0	0
S2-8	6.26E-07	1.00	0	0	0	0	2.88	0	1.00	0	0	0	2.24	0	1.00	0	0	0
S2-9	1.71E-06	1.00	0	0	0	0	2.80	0	1.00	0	0	0	2.52	0	1.00	0	0	0
S2-10	2.85E-06	1.00	0	0	0	0	2.80	0	1.00	0	0	0	2.40	0	1.00	0	0	0
S2-11	3.98E-07	1.00	0	0	0	0	3.04	0	0.96	0.04	0	0	2.16	0	1.00	0	0	0
S2-12	1.94E-05	0	0	0.53	0.47	0	2.72	0	1.00	0	0	0	2.16	0	1.00	0	0	0
S2-13	1.94E-06	1.00	0	0	0	0	2.40	0	1.00	0	0	0	2.24	0	1.00	0	0	0
S2-14	1.82E-06	1.00	0	0	0	0	2.84	0	1.00	0	0	0	2.88	0	1.00	0	0	0
S2-15	1.71E-05	0	0	1.00	0	0	3.36	0	0.64	0.36	0	0	3.04	0	0.96	0.04	0	0
S2-16	2.28E-05	0	0	0	1.00	0	3.52	0	0.48	0.52	0	0	2.96	0	1.00	0	0	0
S2-17	2.49E-05	0	0	0	0	1.00	3.60	0	0.40	0.60	0	0	3.04	0	0.96	0.04	0	0
S2-18	1.14E-05	0	0.20	0.80	0	0	3.36	0	0.64	0.36	0	0	3.52	0	0.48	0.52	0	0
S2-19	5.69E-06	0.90	0.10	0	0	0	3.52	0	0.48	0.52	0	0.00	3.52	0	0.48	0.52	0	0
S2-20	2.28E-05	0	0	0	1.00	0	3.68	0	0.32	0.68	0	0.00	3.20	0	0.80	0.20	0	0
S2-21	2.85E-05	0	0	0	0	1.00	3.52	0	0.48	0.52	0	0.00	3.20	0	0.80	0.20	0	0

Table 7.9 Continue

Sub-Sytem	Component Failure Code	Failure Likelihood						Failure Consequence Severity						Failure Consequence Probability					
		Value	Very Low	Low	Average	High	Very High	Weighted Score	Negligible	Marginal	Moderate	Severe	Catastrophic	Weighted Score	Highly Unlikely	Unlikely	Likely	Highly Likely	Definite
Compressors	CP-1	7.40E-07	1.00	0	0	0	0	2.88	0	1.00	0	0	0	2.36	0	1.00	0	0	0
	CP-2	1.02E-05	0	0.58	0.42	0	0	2.64	0	1.00	0	0	0	2.32	0	1.00	0	0	0
	CP-3	3.42E-07	0	1.00	0	0	0	2.48	0	1.00	0	0	0	2.40	0	1.00	0	0	0
	CP-4	5.12E-06	0.30	0.70	0	0	0	2.80	0	1.00	0	0	0	2.16	0	1.00	0	0	0
	CP-5	5.69E-06	0.10	0.90	0	0	0	2.96	0	1.00	0	0	0	2.64	0	1.00	0	0	0
	CP-6	1.37E-05	0	0	1.00	0	0	2.80	0	1.00	0	0	0	2.72	0	1.00	0	0	0
	CP-7	1.14E-05	0	0.20	0.80	0	0	2.80	0	1.00	0	0	0	2.64	0	1.00	0	0	0
	CP-8	7.97E-06	1.00	0	0	0	0	2.96	0	1.00	0	0	0	2.48	0	1.00	0	0	0
	CP-9	1.14E-06	1.00	0	0	0	0	2.80	0	1.00	0	0	0	2.28	0	1.00	0	0	0
	CP-10	6.83E-06	0	1.00	0	0	0	2.80	0	1.00	0	0	0	2.28	0	1.00	0	0	0
	CP-11	1.71E-05	0	0	1.00	0	0	2.64	0	1	0	0	0	2.64	0	1.00	0	0	0
	CP-12	2.28E-05	0	0		1.00	0	3.04	0	0.96	0.04	0	0	2.72	0	1.00	0	0	0
	CP-13	1.71E-05	0	0	1.00	0	0	3.44	0	0.56	0.44	0	0	3.12	0	0.88	0.12	0	0
	CP-14	2.28E-05	0	0	0	1.00	0	3.28	0	0.72	0.28	0	0	3.12	0	0.88	0.12	0	0
	CP-15	2.85E-05	0	0	0	0	1.00	3.28	0	0.72	0.28	0	0	2.80	0	1.00	0	0	0
	CP-16	1.14E-06	1.00	0	0	0	0	3.20	0	0.80	0.20	0	0	3.28	0	0.72	0.28	0	0
	CP-17	5.69E-07	1.00	0	0	0	0	3.44	0	0.56	0.44	0	0	3.20	0	0.80	0.20	0	0
Flash Drum	FD-1	3.42E-07	1.00	0	0	0	0	2.64	0	1.00	0	0	0	2.32	0	1.00	0	0	0
	FD-2	5.12E-06	0.30	0.70	0	0	0	2.64	0	1.00	0	0	0	2.32	0	1.00	0	0	0
	FD-3	3.42E-07	1.00	0	0	0	0	3.28	0	0.72	0.28	0	0	2.24	0	1.00	0	0	0
	FD-4	8.54E-07	1.00	0	0	0	0	2.80	0	1.00	0	0	0	2.24	0	1.00	0	0	0
	FD-5	3.42E-09	1.00	0	0	0	0	2.64	0	1.00	0	0	0	2.32	0	1.00	0	0	0
	FD-6	5.12E-06	0.30	0.70	0	0	0	2.64	0	1.00	0	0	0	2.32	0	1.00	0	0	0
	FD-7	7.40E-06	0	1.00	0	0	0	2.64	0	1.00	0	0	0	2.48	0	1.00	0	0	0
	FD-8	5.12E-07	1.00	0	0	0	0	2.88	0	1.00	0	0	0	2.72	0	1.00	0	0	0
	FD-9	1.71E-05	0	0	1.00	0	0	3.36	0	0.64	0.36	0	0	3.04	0	0.96	0.04	0	0
	FD-10	2.28E-05	0	0	0	1.00	0	3.60	0	0.40	0.60	0	0	2.96	0	1.00	0	0	0
	FD-11	2.85E-05	0	0	0	0	1.00	3.60	0	0.40	0.60	0	0	2.96	0	1.00	0	0	0
	FD-12	1.71E-05	0	0	1.00	0	0	3.60	0	0.40	0.60	0	0	2.96	0	1.00	0	0	0
	FD-13	2.28E-05	0	0	0	1.00	0	3.60	0	0.40	0.60	0	0	3.04	0	0.96	0.04	0	0
	FD-14	1.71E-05	0	0	1.00	0	0	2.88	0	1.00	0	0	0	2.80	0	1.00	0	0	0
	FD-15	5.69E-06	0.10	0.90	0	0	0	2.88	0	1.00	0	0	0	2.80	0	1.00	0	0	0
Drier	DR-1	2.28E-07	1.00	0	0	0	0	2.00	0	1.00	0	0	0	1.92	0.08	0.92	0	0	0
	DR-2	2.28E-06	1.00	0	0	0	0	2.40	0	1.00	0	0	0	2.24	0	1.00	0	0	0
	DR-3	2.85E-06	1.00	0	0	0	0	2.40	0	1.00	0	0	0	2.24	0	1.00	0	0	0
	DR-4	2.28E-06	1.00	0	0	0	0	2.40	0	1.00	0	0	0	2.48	0	1.00	0	0	0
	DR-5	1.71E-05	0	0	1.00	0	0	2.48	0	1.00	0	0	0	2.72	0	1.00	0	0	0
	DR-6	4.55E-07	1.00	0	0	0	0	2.64	0	1.00	0	0	0	2.60	0	1.00	0	0	0
	DR-7	9.11E-07	1.00	0	0	0	0	2.64	0	1.00	0	0	0	2.56	0	1.00	0	0	0
	DR-8	8.54E-07	1.00	0	0	0	0	3.20	0	0.80	0.20	0	0	3.60	0	0.40	0.60	0	0
	DR-9	1.14E-06	1.00	0	0	0	0	3.36	0	0.64	0.36	0	0	3.60	0	0.40	0.60	0	0
	DR-10	2.28E-05	0	0	0	1.00	0	3.36	0	0.64	0.36	0	0	3.44	0	0.56	0.44	0	0
	DR-11	2.85E-05	0	0	0	0	1.00	3.36	0	0.64	0.36	0	0	3.44	0	0.56	0.44	0	0
	DR-12	1.71E-05	0	0	1.00	0	0	3.44	0	0.56	0.44	0	0	3.52	0	0.48	0.52	0	0
	DR-13	2.28E-05	0	0	0	1.00	0	3.36	0	0.64	0.36	0	0	3.52	0	0.48	0.52	0	0
	DR-14	5.69E-06	0.10	0.90	0	0	0	3.12	0	0.88	0.12	0	0	3.36	0	0.64	0.36	0	0
	DR-15	1.14E-05	0	0.20	0.80	0	0	3.12	0	0.88	0.12	0	0	3.36	0	0.64	0.36	0	0

7.3.5 Effect of third parameter FCP through comparison of KBRAM and TPRAM

It is important to demonstrate the benefit of additional parameter FCP (failure consequence probability) by comparing the results of the proposed risk assessment system with the results from typical two–input parameter fuzzy reasoning approach based risk assessment method (TPRAM). TPRAM has been slightly modified to develop the proposed knowledge-based risk assessment method (KBRAM) for application in the risk assessment of offshore platform. The results produced by both TPRAM and proposed KBRAM methods are enumerated in Table 7.9 for ease of comparison and validation purposes. In this table, the risk level values for both models have been computed using same fuzzy aggregation method with only difference being the modification by the introduction of an additional input parameter (FCP) in the case of the proposed KBRAM. The breakdown of the result presented in Table 7.10 shows that, the proposed KBRAM is seen to have returned more efficient results compared with those produced by TPRAM as demonstrated in subsequent sections. Table 7.11 is produced to further demonstrate the effect of FCP on the result as shown in the section 7.3.6.

Table 7.10 Risk Levels of Component Failures

Sub-Sytem	Component Failure Code	Input Parameter			Output Risk Level									
		KBRAM			KBRAM					TPRAM				
		TPRAM												
		FLH	FCS	FCP	Risk Score	Minor	Tolerable	Major	Intolerable	Risk Score	Minor	Tolerable	Major	Intolerable
Separator 1	S1-1	2.85E-06	3.04	2.24	1.80	100%				4.00		100%		
	S1-2	2.28E-06	2.96	2.24	1.50	100%				4.00		100%		
	S1-3	9.11E-06	2.80	2.48	4.00		100%			4.00		100%		
	S1-4	3.42E-07	3.28	1.84	1.50	100%				4.00		100%		
	S1-5	1.94E-06	2.80	2.56	1.50	100%				4.00		100%		
	S1-6	2.28E-06	3.04	2.56	1.60	100%				4.00		100%		
	S1-7	7.97E-06	2.88	2.56	4.00		100%			4.00		100%		
	S1-8	2.85E-06	3.04	2.40	1.60	100%				4.00		100%		
	S1-9	2.39E-07	2.64	2.64	1.50	100%				4.00		100%		
	S1-10	8.54E-07	3.04	2.64	1.60	100%				4.00		100%		
	S1-11	1.71E-07	3.04	2.56	1.60	100%				4.00		100%		
	S1-12	5.69E-06	3.52	3.12	3.85		100%			4.00		100%		
	S1-13	1.71E-07	3.92	3.04	2.33		100%			4.00		100%		
	S1-14	1.71E-06	3.20	2.24	2.00	100%				4.00		100%		
	S1-15	3.42E-07	3.52	2.56	2.80	16%	84%			4.00		100%		
	S1-16	2.28E-06	3.36	2.56	2.40	56%	44%			4.00		100%		
	S1-17	2.28E-06	3.28	2.72	3.30		100%			4.00		100%		
	S1-18	1.71E-07	4.00	3.12	4.00		100%			4.00		100%		
	S1-19	1.71E-05	4.00	3.04	5.50		46%	54%		7.00			100%	
	S1-20	2.28E-05	4.00	2.96	7.00			100%		9.00				100%
	S1-21	2.85E-05	4.16	2.80	7.00			100%		9.00				100%
Separator 2	S2-1	5.12E-06	2.24	2.24	2.80	16%	84%			4.00		100%		
	S2-2	3.42E-07	2.48	2.08	1.50	100%				4.00		100%		
	S2-3	5.12E-06	2.48	2.32	3.25		100%			4.00		100%		
	S2-4	3.42E-07	2.48	2.16	1.50	100%				4.00		100%		
	S2-5	1.71E-07	2.48	2.20	1.50	100%				4.00		100%		
	S2-6	4.55E-08	2.48	2.20	1.50	100%				4.00		100%		
	S2-7	7.40E-07	2.64	2.36	1.50	100%				4.00		100%		
	S2-8	6.26E-07	2.88	2.24	1.50	100%				4.00		100%		
	S2-9	1.71E-06	2.80	2.52	1.50	100%				4.00		100%		
	S2-10	2.85E-06	2.80	2.40	1.50	100%				4.00		100%		
	S2-11	3.98E-07	3.04	2.16	1.60	100%				4.00		100%		
	S2-12	1.94E-05	2.72	2.16	4.00		100%			4.00		100%		
	S2-13	1.94E-06	2.40	2.24	1.50	100%				4.00		100%		
	S2-14	1.82E-06	2.84	2.88	1.50	100%				7.00		100%		
	S2-15	1.71E-05	3.36	3.04	5.11		85%	15%		4.00		100%		
	S2-16	2.28E-05	3.52	2.96	4.00		100%			5.56		40%	60%	
	S2-17	2.49E-05	3.60	3.04	5.78		18%	82%		9.00				100%
	S2-18	1.14E-05	3.36	3.52	4.95		100%			7.00			100%	
	S2-19	5.69E-06	3.52	3.52	3.56		100%			7.00			100%	
	S2-20	2.28E-05	3.68	3.20	5.89		7%	93%		9.00				100%
	S2-21	2.85E-05	3.52	3.20	5.54		43%	57%		9.00				100%

Table 7.10 Continue

Sub-Sytem	Component Failure Code	Input Parameters			Output Risk Level									
		KBRAM			KBRAM					TPRAM				
		TPRAM												
		FLH	FCS	FCP	Risk Score	Minor	Tolerable	Major	Intolerable	Risk Score	Minor	Tolerable	Major	Intolerable
Compressors	CP-1	7.40E-07	2.88	2.36	1.50	100%				4.00		100%		
	CP-2	1.02E-05	2.64	2.32	4.00		100%			4.00		100%		
	CP-3	3.42E-07	2.48	2.40	4.00		100%			4.00		100%		
	CP-4	5.12E-06	2.80	2.16	3.25		100%			4.00		100%		
	CP-5	5.69E-06	2.96	2.64	3.75		100%			4.00		100%		
	CP-6	1.37E-05	2.80	2.72	4.00		100%			4.00		100%		
	CP-7	1.14E-05	2.80	2.64	4.00		100%			4.00		100%		
	CP-8	7.97E-06	2.96	2.48	4.00		100%			4.00		100%		
	CP-9	1.14E-06	2.80	2.28	1.50	100%				4.00		100%		
	CP-10	6.83E-06	2.80	2.28	4.00		100%			5.20		100%		
	CP-11	1.71E-05	2.64	2.64	4.00		100%			4.00		100%		
	CP-12	2.28E-05	3.04	2.72	4.12		100%			7.00			100%	
	CP-13	1.71E-05	3.44	3.12	5.35		61%	39%		8.80			20%	80%
	CP-14	2.28E-05	3.28	3.12	4.97		100%			7.56			100%	
	CP-15	2.85E-05	3.28	2.80	4.84		100%			7.56			100%	
	CP-16	1.14E-06	3.20	3.28	2.71	25%	75%			3.50		100%		
	CP-17	5.69E-07	3.44	3.20	3.00		100%			3.00			100%	
Flash Drum	FD-1	3.42E-07	2.64	2.32	1.50	100%				4.00		100%		
	FD-2	5.12E-06	2.64	2.32	3.75		100%			3.25		100%		
	FD-3	3.42E-07	3.28	2.24	2.20	77%	23%			3.30		100%		
	FD-4	8.54E-07	2.80	2.24	1.50	100%				4.00		100%		
	FD-5	3.42E-09	2.64	2.32	1.50	100%				4.00		100%		
	FD-6	5.12E-06	2.64	2.32	3.75		100%			3.25		100%		
	FD-7	7.40E-06	2.64	2.48	4.00		100%			7.00			100%	
	FD-8	5.12E-07	2.88	2.72	1.50	100%				4.00		100%		
	FD-9	1.71E-05	3.36	3.04	5.11		85%	15%		6.04			100%	
	FD-10	2.28E-05	3.60	2.96	5.80		16%	84%		7.00			100%	
	FD-11	2.85E-05	3.60	2.96	5.80		16%	84%		8.92			7%	93%
	FD-12	1.71E-05	3.60	2.96	5.80		16%	84%		7.00			100%	
	FD-13	2.28E-05	3.60	3.04	5.22		74%	26%		7.00			93%	7%
	FD-14	1.71E-05	2.88	2.80	4.00		100%			5.92		4%	96%	
	FD-15	5.69E-06	2.88	2.80	3.75		100%			4.30		100%		
Drier	DR-1	2.28E-07	2.00	1.92	1.50	100%				4.00		100%		
	DR-2	2.28E-06	2.40	2.24	1.50	100%				4.00		100%		
	DR-3	2.85E-06	2.40	2.24	1.50	100%				4.00		100%		
	DR-4	2.28E-06	2.40	2.48	1.50	100%				4.00		100%		
	DR-5	1.71E-05	2.48	2.72	4.00		100%			7.00			100%	
	DR-6	4.55E-07	2.64	2.60	1.50	100%				4.00		100%		
	DR-7	9.11E-07	2.64	2.56	1.50	100%				4.00		100%		
	DR-8	8.54E-07	3.20	3.60	3.29		100%			5.60		36%	64%	
	DR-9	1.14E-06	3.36	3.60	3.42		100%			4.00		100%		
	DR-10	2.28E-05	3.36	3.44	5.26		70%	30%		8.28			67%	33%
	DR-11	2.85E-05	3.36	3.44	5.26		70%	30%		8.28			67%	33%
	DR-12	1.71E-05	3.44	3.52	5.40		56%	44%		7.00			100%	
	DR-13	2.28E-05	3.36	3.52	5.26		70%	30%		8.28			67%	33%
	DR-14	5.69E-06	3.12	3.36	3.82		100%			6.38			100%	
	DR-15	1.14E-05	3.12	3.36	4.38		100%			7.00			100%	

7.3.6 Effect on the results when FCP is constant KBRAM and TPRAM

Table 7.10 below shows that when the third parameter FCP (failure consequence probability) is constant the results the results from both methods TPRAM and KBRAM returned the same result.

Table 7.11 Risk Levels of Component Failures when FCP is constant

Sub-Sytem	Component Failure Code	Input Parameter			Output Risk Level									
		KBRAM			KBRAM					TPRAM				
		TPRAM												
		FLH	FCS	FCP	Risk Score	Minor	Tolerable	Major	Intolerable	Risk Score	Minor	Tolerable	Major	Intolerable
Separator 1	S1-1	2.85E-06	3.04	1.00	4.00		100%			4.00		100%		
	S1-2	2.28E-06	2.96	1.00	4.00		100%			4.00		100%		
	S1-3	9.11E-06	2.80	1.00	4.00		100%			4.00		100%		
	S1-4	3.42E-07	3.28	1.00	4.00		100%			4.00		100%		
	S1-5	1.94E-06	2.80	1.00	4.00		100%			4.00		100%		
	S1-6	2.28E-06	3.04	1.00	4.00		100%			4.00		100%		
	S1-7	7.97E-06	2.88	1.00	4.00		100%			4.00		100%		
	S1-8	2.85E-06	3.04	1.00	4.00		100%			4.00		100%		
	S1-9	2.39E-07	2.64	1.00	4.00		100%			4.00		100%		
	S1-10	8.54E-07	3.04	1.00	4.00		100%			4.00		100%		
	S1-11	1.71E-07	3.04	1.00	4.00		100%			4.00		100%		
	S1-12	5.69E-06	3.52	1.00	4.00		100%			4.00		100%		
	S1-13	1.71E-07	3.92	1.00	4.00		100%			4.00		100%		
	S1-14	1.71E-06	3.20	1.00	4.00		100%			4.00		100%		
	S1-15	3.42E-07	3.52	1.00	4.00		100%			4.00		100%		
	S1-16	2.28E-06	3.36	1.00	4.00		100%			4.00		100%		
	S1-17	2.28E-06	3.28	1.00	4.00		100%			4.00		100%		
	S1-18	1.71E-07	4.00	1.00	4.00		100%			4.00		100%		
	S1-19	1.71E-05	4.00	1.00	7.00			100%		7.00			100%	
	S1-20	2.28E-05	4.00	1.00	9.00				100%	9.00				100%
	S1-21	2.85E-05	4.16	1.00	9.00				100%	9.00				100%
Separator 2	S2-1	5.12E-06	2.24	1.00	4.00		100%			4.00		100%		
	S2-2	3.42E-07	2.48	1.00	4.00		100%			4.00		100%		
	S2-3	5.12E-06	2.48	1.00	4.00		100%			4.00		100%		
	S2-4	3.42E-07	2.48	1.00	4.00		100%			4.00		100%		
	S2-5	1.71E-07	2.48	1.00	4.00		100%			4.00		100%		
	S2-6	4.55E-08	2.48	1.00	4.00		100%			4.00		100%		
	S2-7	7.40E-07	2.64	1.00	4.00		100%			4.00		100%		
	S2-8	6.26E-07	2.88	1.00	4.00		100%			4.00		100%		
	S2-9	1.71E-06	2.80	1.00	4.00		100%			4.00		100%		
	S2-10	2.85E-06	2.80	1.00	4.00		100%			4.00		100%		
	S2-11	3.98E-07	3.04	1.00	4.00		100%			4.00		100%		
	S2-12	1.94E-05	2.72	1.00	4.00		100%			4.00		100%		
	S2-13	1.94E-06	2.40	1.00	4.00		100%			4.00		100%		
	S2-14	1.82E-06	2.84	1.00	7.00		100%			7.00		100%		
	S2-15	1.71E-05	3.36	1.00	4.00		100%			4.00		100%		
	S2-16	2.28E-05	3.52	1.00	5.56			40%	60%	5.56			40%	60%
	S2-17	2.49E-05	3.60	1.00	9.00				100%	9.00				100%
	S2-18	1.14E-05	3.36	1.00	7.00			100%		7.00			100%	
	S2-19	5.69E-06	3.52	1.00	7.00			100%		7.00			100%	
	S2-20	2.28E-05	3.68	1.00	9.00				100%	9.00				100%
	S2-21	2.85E-05	3.52	1.00	9.00				100%	9.00				100%

Table 7.11 Continue

Sub-Sytem	Component Failure Code	Input Parameters			Output Risk Level									
		KBRAM			KBRAM					TPRAM				
		TPRAM												
		FLH	FCS	FCP	Risk Score	Minor	Tolerable	Major	Intolerable	Risk Score	Minor	Tolerable	Major	Intolerable
Compressors	CP-1	7.40E-07	2.88	1.00	4.00		100%			4.00		100%		
	CP-2	1.02E-05	2.64	1.00	4.00		100%			4.00		100%		
	CP-3	3.42E-07	2.48	1.00	4.00		100%			4.00		100%		
	CP-4	5.12E-06	2.80	1.00	4.00		100%			4.00		100%		
	CP-5	5.69E-06	2.96	1.00	4.00		100%			4.00		100%		
	CP-6	1.37E-05	2.80	1.00	4.00		100%			4.00		100%		
	CP-7	1.14E-05	2.80	1.00	4.00		100%			4.00		100%		
	CP-8	7.97E-06	2.96	1.00	4.00		100%			4.00		100%		
	CP-9	1.14E-06	2.80	1.00	4.00		100%			4.00		100%		
	CP-10	6.83E-06	2.80	1.00	5.20		100%			5.20		100%		
	CP-11	1.71E-05	2.64	1.00	4.00		100%			4.00		100%		
	CP-12	2.28E-05	3.04	1.00	7.00			100%		7.00			100%	
	CP-13	1.71E-05	3.44	1.00	8.80			20%	80%	8.80			20%	80%
	CP-14	2.28E-05	3.28	1.00	7.56			100%		7.56			100%	
	CP-15	2.85E-05	3.28	1.00	7.56			100%		7.56			100%	
	CP-16	1.14E-06	3.20	1.00	3.50		100%			3.50		100%		
	CP-17	5.69E-07	3.44	1.00	3.00		100%			3.00		100%		
Flash Drum	FD-1	3.42E-07	2.64	1.00	4.00		100%			4.00		100%		
	FD-2	5.12E-06	2.64	1.00	3.25		100%			3.25		100%		
	FD-3	3.42E-07	3.28	1.00	3.30		100%			3.30		100%		
	FD-4	8.54E-07	2.80	1.00	4.00		100%			4.00		100%		
	FD-5	3.42E-09	2.64	1.00	4.00		100%			4.00		100%		
	FD-6	5.12E-06	2.64	1.00	3.25		100%			3.25		100%		
	FD-7	7.40E-06	2.64	1.00	7.00		100%			7.00		100%		
	FD-8	5.12E-07	2.88	1.00	4.00			100%		4.00			100%	
	FD-9	1.71E-05	3.36	1.00	6.04			100%		6.04			100%	
	FD-10	2.28E-05	3.60	1.00	7.00			100%		7.00			100%	
	FD-11	2.85E-05	3.60	1.00	8.92			7%	93%	8.92			7%	93%
	FD-12	1.71E-05	3.60	1.00	7.00			100%		7.00			100%	
	FD-13	2.28E-05	3.60	1.00	7.00			93%	7%	7.00			93%	7%
	FD-14	1.71E-05	2.88	1.00	5.92		4%	96%		5.92		4%	96%	
	FD-15	5.69E-06	2.88	1.00	4.30		100%			4.30		100%		
Drier	DR-1	2.28E-07	2.00	1.00	4.00		100%			4.00		100%		
	DR-2	2.28E-06	2.40	1.00	4.00		100%			4.00		100%		
	DR-3	2.85E-06	2.40	1.00	4.00		100%			4.00		100%		
	DR-4	2.28E-06	2.40	1.00	4.00		100%			4.00		100%		
	DR-5	1.71E-05	2.48	1.00	7.00			100%		7.00			100%	
	DR-6	4.55E-07	2.64	1.00	4.00		100%			4.00		100%		
	DR-7	9.11E-07	2.64	1.00	4.00		100%			4.00		100%		
	DR-8	8.54E-07	3.20	1.00	5.60		36%	64%		5.60		36%	64%	
	DR-9	1.14E-06	3.36	1.00	4.00		100%			4.00		100%		
	DR-10	2.28E-05	3.36	1.00	8.28			67%	33%	8.28			67%	33%
	DR-11	2.85E-05	3.36	1.00	8.28			67%	33%	8.28			67%	33%
	DR-12	1.71E-05	3.44	1.00	7.00			100%		7.00			100%	
	DR-13	2.28E-05	3.36	1.00	8.28			67%	33%	8.28			67%	33%
	DR-14	5.69E-06	3.12	1.00	6.38			100%		6.38			100%	
	DR-15	1.14E-05	3.12	1.00	7.00			100%		7.00			100%	

7.3.7 Result Analysis comparing KBRAM and HAZOPS for Offshore Processing Unit

It is important to note that, there are significant benefits to be gained by comparing the results of the proposed risk assessment system with the results from typical industry adopted HAZOPS assessment method. HAZOPS is currently being used by experts in oil & gas industry. However, as stated in section 2.7.5 of Chapter 2, its reliance on historical data necessitate the need for introduction of such methods like a knowledge-based risk assessment method (KBRAM) for application in the risk assessment of offshore platform has been developed. The results produced by both industry experts using HAZOPS and proposed KBRAM methods are enumerated in Table 7.12 for ease of comparison and validation purposes. The breakdown of the result presented in Table 7.12 shows that, the proposed KBRAM is seen to have returned more detailed results compared with those produced through HAZOPS while maintaining some level of consistency as demonstrated in subsequent sections.

As stated above, the result presented in Table 7.12 revealed that the KBRAM assessment demonstrates a remarkable reduction in the risk level categorisations as compared to HAZOPS. This reduction will translate to corresponding reduction in mitigation requirements and its cost implication. The detail reduction show that by comparing the two results for each of the offshore processing unit sub-systems indicate reduction of 81-90% achieved for Separators, 35% for Compressors, 73% for Flash Drum and 60% for Drier. The detailed analyses are as described in the following sections.

Table 7.12 Risk Levels of Component Failures

Sub-Sytem	Component Failure Code	Input Parameter			Output Risk Level									
		KBRAM			KBRAM					HAZOPS				
		FLH	FCS	FCP	Risk Score	Minor	Tolerable	Major	Intolerable	Risk Score	Minor	Tolerable	Major	Intolerable
Separator 1	S1-1	2.85E-06	3.04	2.24	1.80	100%				3.00		100%		
	S1-2	2.28E-06	2.96	2.24	1.50	100%				2.00	100%			
	S1-3	9.11E-06	2.80	2.48	4.00		100%			3.00		100%		
	S1-4	3.42E-07	3.28	1.84	1.50	100%				4.00		100%		
	S1-5	1.94E-06	2.80	2.56	1.50	100%				6.00			100%	
	S1-6	2.28E-06	3.04	2.56	1.60	100%				7.00			100%	
	S1-7	7.97E-06	2.88	2.56	4.00		100%			4.00		100%		
	S1-8	2.85E-06	3.04	2.40	1.60	100%				3.00		100%		
	S1-9	2.39E-07	2.64	2.64	1.50	100%				4.00		100%		
	S1-10	8.54E-07	3.04	2.64	1.60	100%				3.00		100%		
	S1-11	1.71E-07	3.04	2.56	1.60	100%				5.00		100%		
	S1-12	5.69E-06	3.52	3.12	3.85		100%			7.00			100%	
	S1-13	1.71E-07	3.92	3.04	2.33		100%			5.00		100%		
	S1-14	1.71E-06	3.20	2.24	2.00	100%				2.00	100%			
	S1-15	3.42E-07	3.52	2.56	2.80	16%	84%			6.00			100%	
	S1-16	2.28E-06	3.36	2.56	2.40	56%	44%			7.00			100%	
	S1-17	2.28E-06	3.28	2.72	3.30		100%			6.00			100%	
	S1-18	1.71E-07	4.00	3.12	4.00		100%			8.00			93%	7%
	S1-19	1.71E-05	4.00	3.04	5.50		46%	54%		7.00			100%	
	S1-20	2.28E-05	4.00	2.96	7.00			100%		9.00				100%
	S1-21	2.85E-05	4.16	2.80	7.00			100%		9.00				100%
Separator 2	S2-1	5.12E-06	2.24	2.24	2.80	16%	84%			2.00	100%			
	S2-2	3.42E-07	2.48	2.08	1.50	100%				2.00	100%			
	S2-3	5.12E-06	2.48	2.32	3.25		100%			2.00	100%			
	S2-4	3.42E-07	2.48	2.16	1.50	100%				2.00	100%			
	S2-5	1.71E-07	2.48	2.20	1.50	100%				5.00		100%		
	S2-6	4.55E-08	2.48	2.20	1.50	100%				5.00		100%		
	S2-7	7.40E-07	2.64	2.36	1.50	100%				4.00		100%		
	S2-8	6.26E-07	2.88	2.24	1.50	100%				2.00	100%			
	S2-9	1.71E-06	2.80	2.52	1.50	100%				2.00	100%			
	S2-10	2.85E-06	2.80	2.40	1.50	100%				2.00	100%			
	S2-11	3.98E-07	3.04	2.16	1.60	100%				5.00		100%		
	S2-12	1.94E-05	2.72	2.16	4.00		100%			5.00		100%		
	S2-13	1.94E-06	2.40	2.24	1.50	100%				5.00		100%		
	S2-14	1.82E-06	2.84	2.88	1.50	100%				2.00	100%			
	S2-15	1.71E-05	3.36	3.04	5.11		85%	15%		8.00			100%	
	S2-16	2.28E-05	3.52	2.96	4.00		100%			8.00			100%	
	S2-17	2.49E-05	3.60	3.04	5.78		18%	82%		6.00			100%	
	S2-18	1.14E-05	3.36	3.52	4.95		100%			8.00			93%	7%
	S2-19	5.69E-06	3.52	3.52	3.56		100%			8.00			93%	7%
	S2-20	2.28E-05	3.68	3.20	5.89		7%	93%		9.00				100%
	S2-21	2.85E-05	3.52	3.20	5.54		43%	57%		9.00				100%

Table 7.12 Continue

Sub-Sytem	Component Failure Code	Input Parameters			Output Risk Level									
		KBRAM			KBRAM					HAZOPS				
		FLH	FCS	FCP	Risk Score	Minor	Tolerable	Major	Intolerable	Risk Score	Minor	Tolerable	Major	Intolerable
Compressors	CP-1	7.40E-07	2.88	2.36	1.50	100%				5.00		100%		
	CP-2	1.02E-05	2.64	2.32	4.00		100%			7.00			100%	
	CP-3	3.42E-07	2.48	2.40	4.00		100%			5.00		100%		
	CP-4	5.12E-06	2.80	2.16	3.25		100%			4.00		100%		
	CP-5	5.69E-06	2.96	2.64	3.75		100%			5.00		100%		
	CP-6	1.37E-05	2.80	2.72	4.00		100%			5.00		100%		
	CP-7	1.14E-05	2.80	2.64	4.00		100%			4.00		100%		
	CP-8	7.97E-06	2.96	2.48	4.00		100%			4.00		100%		
	CP-9	1.14E-06	2.80	2.28	1.50	100%				3.00		100%		
	CP-10	6.83E-06	2.80	2.28	4.00		100%			3.00		100%		
	CP-11	1.71E-05	2.64	2.64	4.00		100%			3.00		100%		
	CP-12	2.28E-05	3.04	2.72	4.12		100%			3.00		100%		
	CP-13	1.71E-05	3.44	3.12	5.35		61%	39%		9.00				100%
	CP-14	2.28E-05	3.28	3.12	4.97		100%			8.00			93%	7%
	CP-15	2.85E-05	3.28	2.80	4.84		100%			6.00			100%	
	CP-16	1.14E-06	3.20	3.28	2.71	25%	75%			5.00		100%		
	CP-17	5.69E-07	3.44	3.20	3.00		100%			8.00			93%	7%
Flash Drum	FD-1	3.42E-07	2.64	2.32	1.50	100%				3.00		100%		
	FD-2	5.12E-06	2.64	2.32	3.75		100%			3.00		100%		
	FD-3	3.42E-07	3.28	2.24	2.20	77%	23%			5.00		100%		
	FD-4	8.54E-07	2.80	2.24	1.50	100%				4.00		100%		
	FD-5	3.42E-09	2.64	2.32	1.50	100%				4.00		100%		
	FD-6	5.12E-06	2.64	2.32	3.75		100%			3.00		100%		
	FD-7	7.40E-06	2.64	2.48	4.00		100%			3.00		100%		
	FD-8	5.12E-07	2.88	2.72	1.50	100%				3.00		100%		
	FD-9	1.71E-05	3.36	3.04	5.11		85%	15%		8.00			93%	7%
	FD-10	2.28E-05	3.60	2.96	5.80		16%	84%		7.00			100%	
	FD-11	2.85E-05	3.60	2.96	5.80		16%	84%		8.00			93%	7%
	FD-12	1.71E-05	3.60	2.96	5.80		16%	84%		8.00			93%	7%
	FD-13	2.28E-05	3.60	3.04	5.22		74%	26%		8.00			93%	7%
	FD-14	1.71E-05	2.88	2.80	4.00		100%			6.00			100%	
	FD-15	5.69E-06	2.88	2.80	3.75		100%			5.00		100%		
Drier	DR-1	2.28E-07	2.00	1.92	1.50	100%				4.00		100%		
	DR-2	2.28E-06	2.40	2.24	1.50	100%				5.00		100%		
	DR-3	2.85E-06	2.40	2.24	1.50	100%				5.00		100%		
	DR-4	2.28E-06	2.40	2.48	1.50	100%				5.00		100%		
	DR-5	1.71E-05	2.48	2.72	4.00		100%			6.00			100%	
	DR-6	4.55E-07	2.64	2.60	1.50	100%				4.00		100%		
	DR-7	9.11E-07	2.64	2.56	1.50	100%				6.00		100%		
	DR-8	8.54E-07	3.20	3.60	3.29		100%			8.00		93%	7%	
	DR-9	1.14E-06	3.36	3.60	3.42		100%			8.00		93%	7%	
	DR-10	2.28E-05	3.36	3.44	5.26		70%	30%		9.00				100%
	DR-11	2.85E-05	3.36	3.44	5.26		70%	30%		9.00				100%
	DR-12	1.71E-05	3.44	3.52	5.40		56%	44%		9.00				100%
	DR-13	2.28E-05	3.36	3.52	5.26		70%	30%		9.00				100%
	DR-14	5.69E-06	3.12	3.36	3.82		100%			7.00			100%	
	DR-15	1.14E-05	3.12	3.36	4.38		100%			7.00			100%	

7.3.7.1 Separators

The result of two oil separator (S1) failure events described as S1-20 (ignition due to heat from surrounding) and S1-21 (ignition due to electric spark), and each of these failure events have consequences which could result in the failure leading to possible BLEVE to be followed by fire. It is also important to note in Table 7.12 that both S1-20 and S1-21 have high values of likelihood of failure FLH and, corresponding values of consequence severity (FCS) and consequence probability (FCP), but the two methods recorded major differences in capturing their RL categorisations. While the proposed KBRAM reflected risk levels to belong to major category with a belief of 100 per cent, the traditional HAZOPS system recorded risk levels belonging to intolerable category with a belief of 100 per cent. The HAZOPS results will therefore demand for more costly mitigation efforts.

Further examination of the results in Table 7.12 shows that for separators (S1 & S2) HAZOPS expressed risk levels belonging to a range of values mainly between tolerable and intolerable for most of the component failure events except in the case of two separator 1 events (S1-2 & 14), eight separator 2 events (S2-1, 2, 3, 4, 8, 9, 10 & 14). This in comparison with the results of risk levels obtained from KBRAM are generally categorised lower mainly belonging to between minor and tolerable with exception of seven failure events distributed as three for the separator 1 (SI-19, 20 & 21) and four for the separator 2 (S2-15, 17, 20 & 21).

7.3.7.2 Compressors

For compressors HAZOPS expressed risk levels mainly belonging to the tolerable and major for most of the component failure events except in the case of failure events CP-13 which its risk level categorised to belonging to intolerable with a belief of 100%. In contrast the results posted by KBRAM the risk levels obtained are generally lower belonging mainly to between minor and tolerable with exception of on failure event CP-13 which has its risk level expressed as belonging to tolerable and major categories with a belief of 61% and 39% respectively.

7.3.7.3 Flash Drum

In analysing the results regarding the flash drum component failure events as shown in Table 7.12 it would be observed that, the TPRAM expressed risk levels to belong to the tolerable and major categories for most of the component failure events except for two component failure events (FD-11 & FD-13) having risk level categorised as belonging to intolerable with belief of 93% and 7% respectively. The KBRAM results on other hand maintain lower return of risk levels categorisations belonging to between minor and major but none above that.

7.3.7.4 Drier

Table 7.12 results show that drier component failure events risk levels expressed by HAZOPS to belong to categories between tolerable and major except in the case of failure events (DR-10, 11 12 & 13) which indicate their risk levels to have some degree of belonging in the intolerable category. However, KBRAM results maintained lower categorisations of risk levels belonging to between minor and tolerable with exception of four failure events (DR-10, 11 12 & 13) which are found to belong to major category with belief ranging from 30% to 44%. However, it is interesting to note that, the four component failures events mentioned above have been captured though in different categories but with some level of consistency by both methods.

7.3.7.5 Other results at component level

I. ***High RL events*: -** This is a group of component failure events assessed to have higher risk level belonging to categories of major and intolerable with a belief of 100 per cent. Table 7.12 also shows seventeen failure events falling within this group which include for example S1-21, S2-20, CP-13, FD-10, DR-12 etc.

The above result shows that the failure for example S1-21 and S2-20 have higher failure likelihood (FLH) and moderately high consequence severity and probability which both methods captured but KBRAM returning much more cost effective outcomes. These outcomes are due to additional clarity of information which the third parameter provided.

II. *Low RL events*: - This is a group of component failure events assessed to have lowest risk level belonging to categories of minor and tolerable with a belief of 100 per cent. Table 7.12 also shows KBRAM returned a significant number of failure events falling within this group at the lowest boundary while the traditional method captured most of them at the higher boundary. These results also confirm the quality of information to be higher in the case of KBRAM due to additional in parameter.

This result therefore, demonstrates that the additional input parameter of failure consequence probability (FCP) has provided the proposed KBRAM model with an additional tool needed for a more efficient and effective risk assessment for input with varying combinations compared to the traditional method (HAZOPS). Based on the result thus far it is evident that, the proposed approach performs much better than the traditional method in assessing failure events with different combination of values of FLH or FCS or FCP. It can be concluded therefore that, this outcome satisfies the research aim of providing a more effective risk assessment technique based on cost effective evaluation of providing safety. This further demonstrates that KBRAM could effectively be deployed to facilitate decision making process from very early stages of offshore platform development.

The KBRAM procedure is applied progressively to determine the levels at both sub-system and the overall system level as will be demonstrated in the following section.

7.3.7.6 Results at sub-system level

The results obtained at component levels and discussed in the previous section, are applied to Equation (7-1) shown below to compute risks scores for all the six sub-system and the overall system, and the results tabulated in Tables 7.13, 7.14, 7.15, 7.16 & 7.17. The results obtained revealed some interesting pattern which can be demonstrated for example by comparing the results of two sub-systems i.e. Compressors and Separator 1 (oil). This comparison results show that, the compressor unit despite its moderate damage causing capabilities is still rated to be very risky due to the high likelihood of failure of its components. In contrast however, the separator 1 though rated to be comparatively more hazardous in terms of damage computations but found to be relatively less risky, due to the lower likelihood of failure of its components. Further examination of the aggregated individual sub-unit risk scores and their corresponding risk levels reveals that the compressor poses the highest major individual risk to the entire offshore processing system followed by flash drum and drier units. The individual sub-systems contribution to the overall system risk was computed and the result show that the compressors alone contribute over 35 percent, while separator 2 has the lowest contribution of only 15 percent. Generally these sub-systems risk values exceed the acceptable level based on laid down criteria, this may therefore necessitate design review if considered to be cost effective or to bring within the ALARP region where necessary.

$$Z_{Sub-System} = \frac{\sum_{i=1}^{n} \alpha_i \mu_{B^i}(y)}{\sum_{i=1}^{n} \alpha_i} \tag{7-1}$$

where $i =$ fired rule (1,2,….*n*), $n =$ number of fired rules, $\alpha_i =$ firing strength of the *i-th* rule, $\mu_{B^i}(y)$ MF of risk implication of *i-th* rule $Z_{sub-system} =$ sub-system risk score

Table 7.13 Sub-System Risk Level – Separator 1

Separator 1						
Fired Rule	Firing strength	Rule Output - RL				MF Implication
		Minor	Tolerable	Major	Intolerable	
R_i	α_i	1.50	4.00	7.00	9.00	$\alpha_i \mu_{B^i}(y)$
R27	0.30	0.45				0.45
R28	0.04		0.16			0.16
R32	0.70		2.80			2.80
R33	0.04		0.16			0.16
R27	0.17	0.26				0.26
R28	0.83		3.32			3.32
R32	0.96		3.84			3.84
R37	0.04		0.16			0.16
R2	0.28	0.42				0.42
R3	0.16	0.24				0.24
R27	0.28		1.12			1.12
R28	0.72		2.88			2.88
R27	0.90	1.35				1.35
R32	0.10		0.40			0.40
R27	0.17	0.26				0.26
R28	0.04		0.16			0.16
R32	0.83		3.32			3.32
R33	0.04		0.16			0.16
R32	1.00		4.00			4.00
R27	0.30	0.45				0.45
R28	0.04		0.16			0.16
R32	0.70		2.80			2.80
R33	0.70		2.80			2.80
R27	1.00	1.50				1.50
R27	0.96	1.44				1.44
R28	0.04		0.16			0.16
R27	0.96	1.44				1.44
R28	0.04		0.16			0.16
R27	0.10	0.15				0.15
R28	0.10		0.40			0.40
R32	0.48		1.92			1.92
R33	0.52		2.08			2.08
R52	0.10		0.40			0.40
R53	0.10		0.40			0.40
R57	0.12		0.48			0.48
R58	0.12		0.48			0.48
R27	0.08	0.12				0.12
R28	0.92		3.68			3.68
R52	0.04		0.16			0.16
R53	0.04		0.16			0.16
R27	0.80	1.20				1.20
R28	0.20		0.80			0.80
R27	0.48	0.72				0.72
R28	0.52		2.08			2.08
R27	0.17	0.26				0.26
R28	0.17		0.68			0.68
R32	0.64		2.56			2.56
R33	0.36		1.44			1.44
R27	0.17	0.26				0.26
R28	0.17		0.68			0.68
R32	0.28		1.12			1.12
R33	0.72		2.88			2.88
R28	0.88	1.32				1.32
R53	0.12		0.48			0.48
R38	0.87			6.09		6.09
R43	0.13			0.91		0.91
R63	0.04			0.28		0.28
R68	0.04			0.28		0.28
R43	1.00			7.00		7.00
R43	0.01			0.07		0.07
R48	0.99			6.93		6.93
$\sum_{i=1}^{n}$	**23.82**	11.82	51.44	21.56		**84.82**
	$Z_{Sub-System}$				**3.56**	

Table 7.14 Sub-System Risk Level – Separator 2

Separator 2						
Fired Rule	Firing strength	Rule Output - RL				MF Implication
R_i	α_i	Minor	Tolerable	Major	Intolerable	$\alpha_i \mu_{B^i}(y)$
		1.50	4.00	7.00	9.00	
R27	0.30	0.45				0.45
R28	0.70		2.80			2.80
R27	1.00	1.50				1.50
R27	0.30	0.45				0.45
R28	0.70		2.80			2.80
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	0.96	1.44				1.44
R28	0.04		0.16			0.16
R37	0.55		2.20			2.20
R42	0.45		1.80			1.80
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R37	0.64		2.56			2.56
R38	0.36			2.52		2.52
R62	0.04		0.16			0.16
R63	0.04			0.28		0.28
R42	0.48		1.92			1.92
R43	0.52		2.08			2.08
R47	0.40		1.60			1.60
R48	0.60			4.20		4.20
R72	0.04		0.16			0.16
R73	0.04			0.28		0.28
R32	0.21		0.84			0.84
R33	0.21		0.84			0.84
R37	0.48		1.92			1.92
R38	0.48			3.36		3.36
R57	0.21		0.84			0.84
R58	0.21		0.84			0.84
R62	0.52		2.08			2.08
R63	0.36			2.52		2.52
R27	0.48	0.72				0.72
R28	0.48		1.92			1.92
R32	0.10		0.40			0.40
R33	0.10		0.40			0.40
R52	0.48		1.92			1.92
R53	0.52		2.08			2.08
R57	0.48		1.92			1.92
R58	0.10		0.40			0.40
R42	0.32		1.28			1.28
R43	0.68			4.76		4.76
R67	0.20		0.80			0.80
R68	0.20			1.40		1.40
R47	0.48		1.92			1.92
R48	0.52			3.64		3.64
R72	0.20		0.80			0.80
R73	0.20			1.40		1.40
$\sum_{i=1}^{n}$	**25.38**	18.06	39.44	24.36		**81.86**
	$Z_{Sub-System}$				**3.23**	

Table 7.15 Sub-System Risk Level - Compressors

Compressors						
Fired Rule R_i	Firing strength α_i	Rule Output - RL				MF Implication $\alpha_i \mu_{B^i}(y)$
		Minor	Tolerable	Major	Intolerable	
		1.50	4.00	7.00	9.00	
R27	1.00	1.50				1.50
R32	0.58		2.32			2.32
R37	0.42		1.68			1.68
R32	1.00		4.00			4.00
R27	0.29	0.44				0.44
R32	0.71		2.84			2.84
R27	0.10	0.15				0.15
R32	0.90		3.60			3.60
R37	1.00		4.00			4.00
R32	0.21		0.84			0.84
R37	0.79		3.16			3.16
R32	1.00		4.00			4.00
R27	1.00		4.00			4.00
R32	1.00		4.00			4.00
R37	1.00		4.00			4.00
R42	0.96		3.84			3.84
R43	0.04			0.28		0.28
R37	0.56		2.24			2.24
R38	0.44			3.08		3.08
R62	0.12		0.48			0.48
R63	0.12			0.84		0.84
R42	0.72		2.88			2.88
R43	0.28			1.96		1.96
R67	0.12		0.48			0.48
R68	0.12			0.84		0.84
R47	0.72		2.88			2.88
R48	0.28			1.96		1.96
R27	0.72	1.08				1.08
R28	0.20		0.80			0.80
R52	0.28		1.12			1.12
R53	0.20		0.80			0.80
R27	0.56	0.84				0.84
R28	0.44		1.76			1.76
R52	0.20		0.80			0.80
R53	0.20		0.80			0.80
$\sum_{i=1}^{n}$	**18.28**	4.01	57.32	8.96		**70.29**
	$Z_{Sub-System}$				**3.84**	

Table 7.16 Sub-System Risk Level – Flash Drum

Flash Drum						
Fired Rule R_i	Firing strength α_i	Rule Output - RL				MF Implication $\alpha_i \mu_{B^i}(y)$
		Minor	Tolerable	Major	Intolerable	
		1.50	4.00	7.00	9.00	
R27	1.00	1.50				1.50
R27	0.29	0.44				0.44
R32	0.71		2.84			2.84
R27	0.72	1.08				1.08
R28	0.28		1.12			1.12
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R32	1.00		4.00			4.00
R27	1.00	1.50				1.50
R37	0.64		2.56			2.56
R38	0.36			2.52		2.52
R62	0.04		0.16			0.16
R63	0.04			0.28		0.28
R42	0.40		1.60			1.60
R43	0.60			4.20		4.20
R47	0.40		1.60			1.60
R48	0.60			4.20		4.20
R37	0.40		1.60			1.60
R38	0.60			4.20		4.20
R42	0.60		2.40			2.40
R43	0.40			2.80		2.80
R67	0.04		0.16			0.16
R68	0.04			0.28		0.28
R37	1.00		4.00			4.00
R27	0.10	0.15				0.15
R32	0.90		3.60			3.60
$\sum_{i=1}^{n}$	**15.16**	9.17	25.64	18.48		**53.29**
	$Z_{Sub-System}$				**3.51**	

Table 7.17 Sub-System Risk Level - Drier

Drier						
Fired Rule	Firing strength	Rule Output - RL				MF Implication
		Minor	Tolerable	Major	Intolerable	
R_i	α_i					$\alpha_i \mu_{B^i}(y)$
		1.50	4.00	7.00	9.00	
R2	0.08	0.12				0.12
R27	0.92	1.38				1.38
R27	0.92	1.38				1.38
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R37	1.00		4.00			4.00
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	0.40	0.60				0.60
R28	0.20		0.80			0.80
R52	0.60		2.40			2.40
R53	0.20		0.80			0.80
R27	0.40	0.60				0.60
R28	0.36		1.44			1.44
R52	0.60		2.40			2.40
R53	0.36		1.44			1.44
R42	0.56		2.24			2.24
R43	0.36			2.52		2.52
R67	0.44		1.76			1.76
R68	0.36			2.52		2.52
R47	0.56		2.24			2.24
R48	0.36			2.52		2.52
R72	0.44		1.76			1.76
R73	0.36			2.52		2.52
R37	0.48		1.92			1.92
R38	0.44			3.08		3.08
R67	0.52		2.08			2.08
R68	0.44			3.08		3.08
R42	0.48		1.92			1.92
R43	0.36			2.52		2.52
R67	0.52		2.08			2.08
R68	0.36			2.52		2.52
R27	0.10	0.15				0.15
R28	0.10		0.40			0.40
R32	0.64		2.56			2.56
R33	0.12		0.48			0.48
R52	0.10		0.40			0.40
R53	0.10		0.40			0.40
R57	0.12		0.48			0.48
R58	0.12		0.48			0.48
R32	0.21		0.84			0.84
R33	0.12		0.48			0.48
R37	0.64		2.56			2.56
R38	0.12			0.84		0.84
R57	0.21		0.84			0.84
R58	0.12		0.48			0.48
R61	0.36		1.44			1.44
R62	0.12			0.84		0.84
$\sum_{i=1}^{n}$	**20.38**	10.23	41.12	22.96		**74.31**
	$Z_{Sub-System}$				**3.65**	

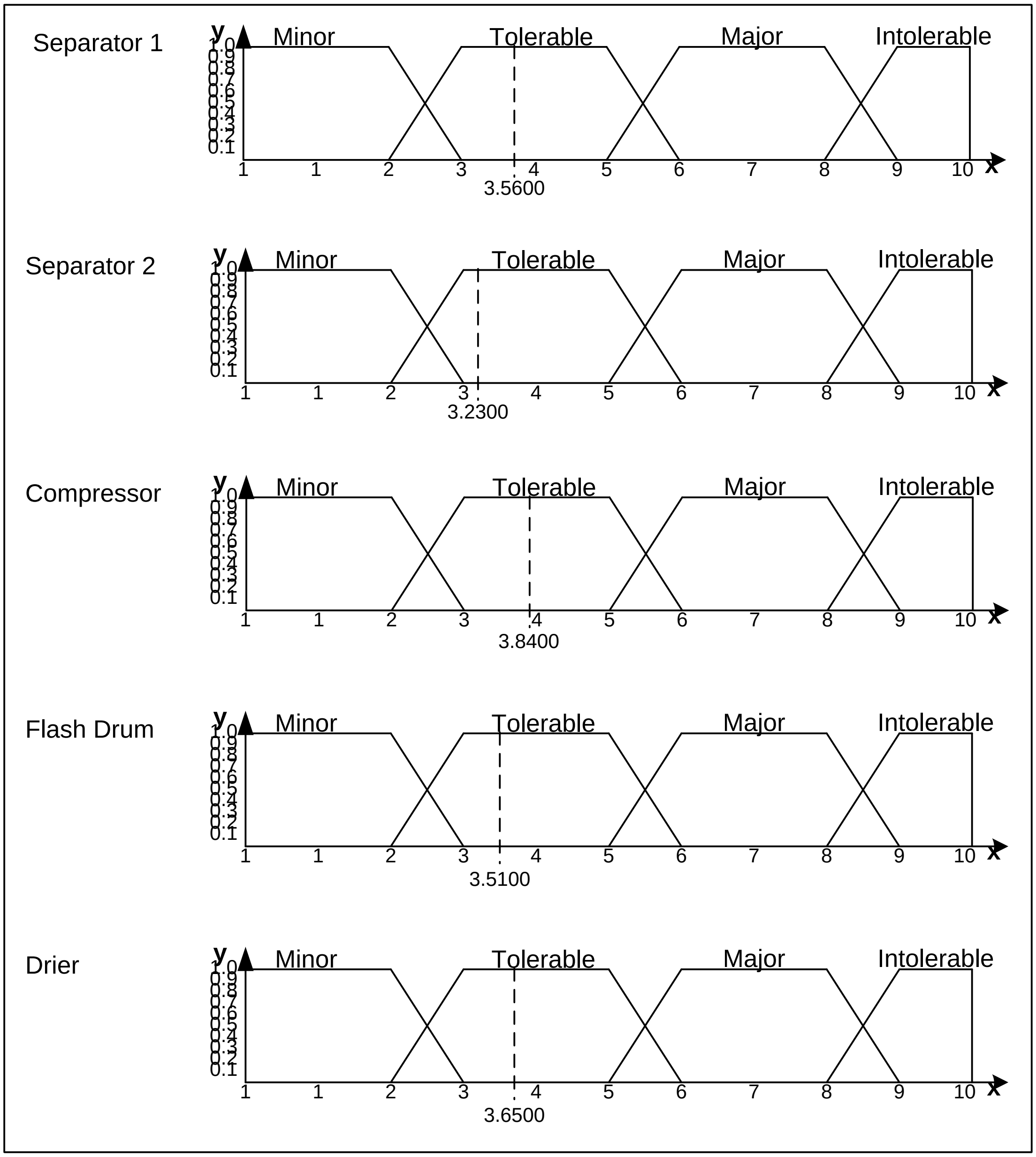

Fig.7.10: Risk level (RL) results at Sub-System Level

7.3.7.7 Results at overall system level

Computing the risk score at the overall system level is achieved by substituting $Z_{sub-system}$ with Z_{system} and considering n being total number of all the fired rules from the six sub-systems, and applying same in Equation (7-1) to obtain the value given in Table 7.18 as shown in the following pages.

This computation gave the overall risk level (RL) of an offshore processing unit (OPU) system as 3.55 belonging to risk category of tolerable with belief of 100 per cent. As mentioned in the previous section there are six identified hazard groups which contribute to the overall RL estimation for OPU system.

Table 7.18 System Risk Level - OPU

Offshore Processing Unit						
Fired Rule	Firing strength	Rule Output - RL				MF Implication
		Minor	Tolerable	Major	Intolerable	
R_i	α_i	1.50	4.00	7.00	9.00	$\alpha_i \mu_{B^i}(y)$
R27	0.30	0.45				0.45
R28	0.04		0.16			0.16
R32	0.70		2.80			2.80
R33	0.04		0.16			0.16
R27	0.17	0.26				0.26
R28	0.83		3.32			3.32
R32	0.96		3.84			3.84
R37	0.04		0.16			0.16
R2	0.28	0.42				0.42
R3	0.16	0.24				0.24
R27	0.28		1.12			1.12
R28	0.72		2.88			2.88
R27	0.90	1.35				1.35
R32	0.10		0.40			0.40
R27	0.17	0.26				0.26
R28	0.04		0.16			0.16
R32	0.83		3.32			3.32
R33	0.04		0.16			0.16
R32	1.00		4.00			4.00
R27	0.30	0.45				0.45
R28	0.04		0.16			0.16
R32	0.70		2.80			2.80
R33	0.70		2.80			2.80
R27	1.00	1.50				1.50
R27	0.96	1.44				1.44
R28	0.04		0.16			0.16
R27	0.96	1.44				1.44
R28	0.04		0.16			0.16
R27	0.10	0.15				0.15
R28	0.10		0.40			0.40
R32	0.48		1.92			1.92
R33	0.52		2.08			2.08
R52	0.10		0.40			0.40
R53	0.10		0.40			0.40
R57	0.12		0.48			0.48
R58	0.12		0.48			0.48
R27	0.08	0.12				0.12
R28	0.92		3.68			3.68
R52	0.04		0.16			0.16
R53	0.04		0.16			0.16
R27	0.80	1.20				1.20
R28	0.20		0.80			0.80
R27	0.48	0.72				0.72
R28	0.52		2.08			2.08
R27	0.17	0.26				0.26
R28	0.17		0.68			0.68
R32	0.64		2.56			2.56
R33	0.36		1.44			1.44
R27	0.17	0.26				0.26
R28	0.17		0.68			0.68
R32	0.28		1.12			1.12
R33	0.72		2.88			2.88
R28	0.88	1.32				1.32

Table 7.18 Continue

Offshore Processing Unit						
Fired Rule	Firing strength	Rule Output - RL				MF Implication
		Minor	Tolerable	Major	Intolerable	
R_i	α_i	1.50	4.00	7.00	9.00	$\alpha_i \mu_{B^i}(y)$
R53	0.12		0.48			0.48
R38	0.87			6.09		6.09
R43	0.13			0.91		0.91
R63	0.04			0.28		0.28
R68	0.04			0.28		0.28
R43	1.00			7.00		7.00
R43	0.01			0.07		0.07
R48	0.99			6.93		6.93
R27	0.30	0.45				0.45
R28	0.70		2.80			2.80
R27	1.00	1.50				1.50
R27	0.30	0.45				0.45
R28	0.70		2.80			2.80
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	0.96	1.44				1.44
R28	0.04		0.16			0.16
R37	0.55		2.20			2.20
R42	0.45		1.80			1.80
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R37	0.64		2.56			2.56
R38	0.36			2.52		2.52
R62	0.04		0.16			0.16
R63	0.04			0.28		0.28
R42	0.48		1.92			1.92
R43	0.52		2.08			2.08
R47	0.40		1.60			1.60
R48	0.60			4.20		4.20
R72	0.04		0.16			0.16
R73	0.04			0.28		0.28
R32	0.21		0.84			0.84
R33	0.21		0.84			0.84
R37	0.48		1.92			1.92
R38	0.48			3.36		3.36
R57	0.21		0.84			0.84
R58	0.21		0.84			0.84
R62	0.52		2.08			2.08
R63	0.36			2.52		2.52
R27	0.48	0.72				0.72
R28	0.48		1.92			1.92
R32	0.10		0.40			0.40
R33	0.10		0.40			0.40
R52	0.48		1.92			1.92
R53	0.52		2.08			2.08
R57	0.48		1.92			1.92
R58	0.10		0.40			0.40
R42	0.32		1.28			1.28
R43	0.68			4.76		4.76
R67	0.20		0.80			0.80
R68	0.20			1.40		1.40
R47	0.48		1.92			1.92
R48	0.52			3.64		3.64
R72	0.20		0.80			0.80

Table 7.18 Continue

Offshore Processing Unit						
Fired Rule	Firing strength	Rule Output - RL				MF Implication
		Minor	Tolerable	Major	Intolerable	
R_i	α_i	1.50	4.00	7.00	9.00	$\alpha_i \mu_{B^i}(y)$
R73	0.20			1.40		1.40
R27	1.00	1.50				1.50
R32	0.58		2.32			2.32
R37	0.42		1.68			1.68
R32	1.00		4.00			4.00
R27	0.29	0.44				0.44
R32	0.71		2.84			2.84
R27	0.10	0.15				0.15
R32	0.90		3.60			3.60
R37	1.00		4.00			4.00
R32	0.21		0.84			0.84
R37	0.79		3.16			3.16
R32	1.00		4.00			4.00
R27	1.00		4.00			4.00
R32	1.00		4.00			4.00
R37	1.00		4.00			4.00
R42	0.96		3.84			3.84
R43	0.04			0.28		0.28
R37	0.56		2.24			2.24
R38	0.44			3.08		3.08
R62	0.12		0.48			0.48
R63	0.12			0.84		0.84
R42	0.72		2.88			2.88
R43	0.28			1.96		1.96
R67	0.12		0.48			0.48
R68	0.12			0.84		0.84
R47	0.72		2.88			2.88
R48	0.28			1.96		1.96
R27	0.72	1.08				1.08
R28	0.20		0.80			0.80
R52	0.28		1.12			1.12
R53	0.20		0.80			0.80
R27	0.56	0.84				0.84
R28	0.44		1.76			1.76
R52	0.20		0.80			0.80
R53	0.20		0.80			0.80
R27	1.00	1.50				1.50
R27	0.29	0.44				0.44
R32	0.71		2.84			2.84
R27	0.72	1.08				1.08
R28	0.28		1.12			1.12
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R32	1.00		4.00			4.00
R27	1.00	1.50				1.50
R37	0.64		2.56			2.56
R38	0.36			2.52		2.52
R62	0.04		0.16			0.16
R63	0.04			0.28		0.28
R42	0.40		1.60			1.60
R43	0.60			4.20		4.20
R47	0.40		1.60			1.60
R48	0.60			4.20		4.20
R37	0.40		1.60			1.60
R38	0.60			4.20		4.20
R42	0.60		2.40			2.40
R43	0.40			2.80		2.80
R67	0.04		0.16			0.16

Table 7.18 Continue

Offshore Processing Unit						
Fired Rule	Firing strength	Rule Output - RL				MF Implication
		Minor	Tolerable	Major	Intolerable	
R_i	α_i	1.50	4.00	7.00	9.00	$\alpha_i \mu_{B^i}(y)$
R68	0.04			0.28		0.28
R37	1.00		4.00			4.00
R27	0.10	0.15		0.70		0.85
R32	0.90		3.60			3.60
R2	0.08	0.12				0.12
R27	0.92	1.38				1.38
R27	0.92	1.38				1.38
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R37	1.00		4.00			4.00
R27	1.00	1.50				1.50
R27	1.00	1.50				1.50
R27	0.40	0.60				0.60
R28	0.20		0.80			0.80
R52	0.60		2.40			2.40
R53	0.20		0.80			0.80
R27	0.40	0.60				0.60
R28	0.36		1.44			1.44
R52	0.60		2.40			2.40
R53	0.36		1.44			1.44
R42	0.56		2.24			2.24
R43	0.36			2.52		2.52
R67	0.44		1.76			1.76
R68	0.36			2.52		2.52
R47	0.56		2.24			2.24
R48	0.36			2.52		2.52
R72	0.44		1.76			1.76
R73	0.36			2.52		2.52
R37	0.48		1.92			1.92
R38	0.44			3.08		3.08
R67	0.52		2.08			2.08
R68	0.44			3.08		3.08
R42	0.48		1.92			1.92
R43	0.36			2.52		2.52
R67	0.52		2.08			2.08
R68	0.36			2.52		2.52
R27	0.10	0.15				0.15
R28	0.10		0.40			0.40
R32	0.64		2.56			2.56
R33	0.12		0.48			0.48
R52	0.10		0.40			0.40
R53	0.10		0.40			0.40
R57	0.12		0.48			0.48
R58	0.12		0.48			0.48
R32	0.21		0.84			0.84
R33	0.12		0.48			0.48
R37	0.64		2.56			2.56
R38	0.12			0.84		0.84
R57	0.21		0.84			0.84
R58	0.12		0.48			0.48
R61	0.36		1.44			1.44
R62	0.12			0.84		0.84
$\sum_{i=1}^{n}$	**103.02**	53.28	214.96	97.02		**365.26**
	Z_{System}				**3.55**	

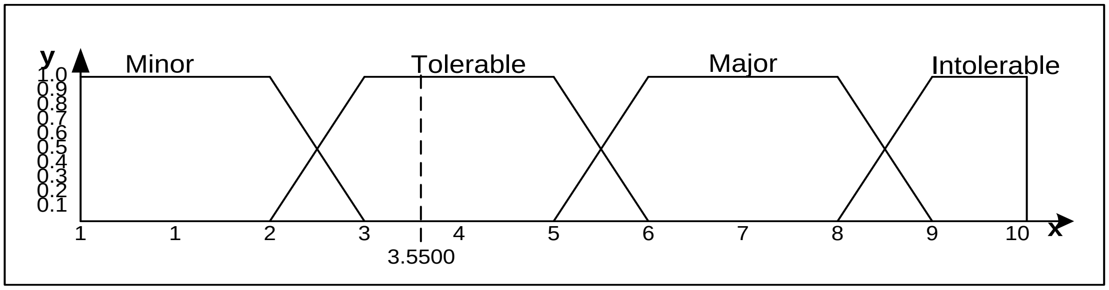

Fig.7.10: Risk level (RL) result at Overall System Level

7.3.7.8 Summary of risk level results at both sub-system and system levels

The risk levels of all the contributing sub-systems and the overall system are summarised in Table 7.19 as shown below for ease of reference.

Table 7.19 Sub-System/ System Risk Levels - Summary

	Sub-Sytem	Assigned Code	Rule Output - RL				
			MF	Linguistic Category			
				Minor	Tolerable	Major	Intolerable
Overall System	Separator 1	SP-1	3.56		100%		
	Separator 2	SP-2	3.23		100%		
	Compressors	CP	3.84		100%		
	Flash Drum	FD	3.51		100%		
	Drier	DR	3.65		100%		
Offshore Processing Unit		**OPU**	**3.55**		**100%**		

7.3.8 Risk Response for Offshore Processing Unit

This is a safety control stage where decisions would be needed in order to proceed with implementation of safety recommendations based on the results of risk assessment. These controls must however, be guided by standard guidelines based on industry regulatory requirement and management policies.

It is important to note that each of the above referred hazard group contributes a different weight value to the overall RL at the system level. The major contributions are from the hazard groups of compressors, flash drum and drier, which contributed to the overall RL of system failure 35, 17 and 17 per cents respectively. Each of these groups consists of a number of hazardous events, for instance, each compressor has seventeen main hazardous or component failure events as listed in Table 7.2 and any of these events could lead to failure of the sub-system, and by extension to the overall system. The documentation on accident and incident reports, and statistics, indicates that significant number of failure events can be traced to design and installation errors such as defective or improper pipes, vessels and jointing. Therefore, in order to make the system safer, it is necessary to reduce risk levels (RLs) of compressor failures which the safety analysts, designers and engineers must harmonise their expertise in order to ensure proper and adequate specifications are incorporated in the designs, and installations are strictly supervised to guarantee compliance with standard.

Further to the above, the operatives must be provided with comprehensive training to enable them interpret as-built drawings and, operational and maintenance manuals in order to be more proactive in dealing with happenings such as leaks, ignition etc. The other potential control measures required to reduce such risks include pipeline maintenance, inspection training of field staff for reducing pipelines related faults, conduct of routine inspection to ensure vessels coming to the terminal are in compliance with safety standard requirements to ensure risk of leaks are controlled, also training of field staff for pipeline maintenance and inspection to further ensure the entire field is covered. Additional security measures will include the provision of access and or egress surveillance system to cover the entire offshore platform, pipeline network to put check on sabotage and/or malicious activities. Also recommended to the industry are additional control measures to reduce other hazardous events in other hazard groups as well as the proposal for a strategy for each additional control. Although the hazard groups of separator 1 and separator 2 contributions of 16 and 15 per cents respectively combined together is still lower than the compressor group mentioned above. However despite the groups' minor contributions to the overall risk level (RL) of offshore processing system, the control measures are still recommended to reduce those hazardous events if considered to be cost effective. Result analysis has shown that the major compressor related hazardous event is the releases from impeller leading to hazard posed through the release of chemicals and thus suggest control measures to include provision of periodic maintenance and inspection of impeller, training operational staff and conduct of regular environmental monitoring.

The case study of offshore processing system has demonstrated that there are potential benefits brought by the application of proposed knowledge-based risk assessment method (KBRAM). KBRAM proved to have the ability to process expert knowledge, engineering judgments, and historical data for the offshore oil and gas safety, and risk assessment in a consistent manner. It has been demonstrated that the proposed method can assess risks directly using the qualitative descriptions that are considered more expressive and natural in describing the risk matters. Also the application of expert contribution factor using the principles of fuzzy reasoning approach will further enhance the treatment of the problems of uncertainties or vagueness in the risk data. As mentioned earlier this procedure of risk assessment is applied progressively to enable the process to progress from hazardous (component) event level to the overall system level.

The case study results which are presented in Tables 7.10, 7.11 & 7.12 have demonstrated that the proposed KBRA Method offers some benefits in the assessment of risk for offshore processing facilities. This result will provide offshore oil and gas safety analysts, operators, engineers, and managers with an additional tool needed to improve safety management and set safety standards. The advantages or merits of this method will encourage safety cost evaluation and facilitate decision making from the design stage of offshore oil and gas platform.

7.4 Summary

This Chapter presents a case study on risk assessment of an offshore processing unit and demonstrates how the proposed modified fuzzy reasoning approach method (KBRAM) can be used to analyse associated risk through a systematic assessment modeling. As stated earlier fuzzy reasoning approach offers a great potential in risk assessment modeling of offshore oil and gas systems, especially in dealing with the risk data which is incomplete or has high level of uncertainty. It was also mentioned in Chapter 6 that risk analysis using fuzzy reasoning approach allows the flexibility required to formulate and incorporate experts' experience and knowledge of risk management in their areas of operation to determine the likelihood of failure and its possible consequences. In addition this flexibility encourages the use of information from various sources to be transformed into knowledge base such as qualitative descriptions, membership functions (MFs) and fuzzy rules as used in the fuzzy inference process.

The process illustrates how the application of the various knowledge acquisition techniques could be deployed to develop fuzzy qualitative descriptions and corresponding MFs to qualify RLs. This prototype model is tested in the current work through a case study to assess the risks associated with a typical offshore processing plant.

The benefit of additional parameter FCP (failure consequence probability) was demonstrated through the comparison of the results from typical two parameter fuzzy reasoning approach based risk assessment method (TPRAM) and the proposed knowledge-based risk assessment method

(KBRAM) for application in the risk assessment of offshore platform for the purposes validation the new model. The breakdown of the result presented in Table 7.9 shows that, the proposed KBRAM is seen to have returned more efficient results compared with those produced by TPRAM as demonstrated in subsequent sections. Table 7.10 is produced to further demonstrate the effect of FCP on the result as shown in the section 7.3.5. This Table shows that when the third parameter FCP (failure consequence probability) is constant the results from both methods are the same.

Internal validation of experts score extracted from the raw data was used to confirm the consistency of fuzzy knowledge-based method (KBRAM) thus deomstarting the reliability of the model as shown in Tables 7.7 & 7.8and Figures 7.7 & 7.8 using typical and disperse expert scores respectively.

The offshore processing unit risk assessment has been conducted to evaluate and validate the performance of the proposed model especially when compared with the results obtained from industry HAZOPS using the same data as shown in Table 7.12. It is important to note that the results obtained using HAZOPS generally expressed higher level of risk compared to those returned by the KBRAM. These results therefore, confirmed that there is an improved efficiency achieved through modification of HAZOPS to develop KBRAM. Considering the reliability of HAZOPS especially in dealing with the uncertainties this modification will even make the result of KBRAM much more reliable and acceptable by offshore oil and gas, and other related industries that have already validated the HAZOPS.

CHAPTER 8

Conclusions and Recommendations

8.1 Background

As stated in the introduction, this research is about the need for further examination of risks associated with offshore oil and gas facilities and their possible causes. This effort is to enable the development of proposed risk assessment method design to compliment other existing methods in the improvement of safety and its management within industrial settings with particular interest in offshore oil and gas platform.

Major inherent risks in the oil and gas industry directly affect people, property and environment as a result of occurrence of any major accident or incident. Previous hazard identification works within the industry confirmed the high-risk scenarios of these types of accidents (Khan *et al*, 2002b).

Review of some previous accidents and incidents related to the offshore operations over the years, revealed the need for continuous improvement in safety management. To assess how this can be effectively achieved, it is pertinent to note the vital roles of knowledge on the nature and causes of these accidents, thus, making risk analysis process very necessary means of ensuring compliance with statutory requirements and related regulatory standards.

It is important to note the need to summarise major highlights of the entire report in the background section of this Chapter before going to the general conclusions, recommendations and future works.

8.1.1 Offshore Platform Safety

Offshore platform safety is a very complicated subject characterised by several factors including operational, human and environmental. As mentioned earlier in this report risk assessment techniques currently being used in the industry are comparatively mature tools, but in many instances, their applications may not give satisfactory results due to incomplete risk information and its associated high level of uncertainty. However, to deal effectively with uncertainties and other related problems, this project proposed a risk assessment methodology for conducting systematic risk assessment using a combination of concept of design for safety and principles of fuzzy reasoning approach (FRA). As enumerated in Chapters 6 & 7 this method employed qualitative descriptors to describe likelihood of failure, consequence severity, consequence probability and risk level. The proposed risk assessment method was applied to evaluate both qualitative and quantitative risk data, and information associated with offshore platform operation efficiently and effectively. The outcomes of risk assessment are represented as the risk degrees and the defined risk categories of risk levels (RLs) with a belief of percentage, which provides very useful risk information to decision makers. This information also provides risk analysts, managers, and engineers with additional technique for the improvement of safety management and set safety standards. In Chapter 7 a case study of risk assessment of offshore processing unit is used to illustrate the application of the proposed methodology.

8.1.2 Assessment of Offshore Platform Risk

The highlights above have been applied in the development of risk assessment process conducted to determine the risk magnitude in order to facilitate safety decision-making. As stated earlier, several oil & gas risk assessment techniques currently used are comparatively mature tools. The results of using these tools highly rely on the availability and accuracy of the risk data (An *et al*, 2006). However, oil & gas safety analysts are often confronted with situation where the risk data is incomplete or is associated with a high level of uncertainty. Furthermore, there are numerous variables interacting in a complex manner that due to the vast amount of data available cannot be explicitly described by a set of equations or a set of rules. There may also be shortage of key information and/or excess of other information. In many instances, it may be extremely difficult to conduct probabilistic risk assessment to assess the occurrence likelihood of hazards and the magnitudes of their possible consequences due to the uncertainty with risk data. It therefore, becomes necessary to develop new risk analysis methods for the identification and assessment of their associated risks in an acceptable way in situations where such mature tools cannot be effectively or efficiently applied (An *et al*, 2007). At this point, the offshore platform safety problem is deemed appropriate for examination using the concept of design for safety combined with fuzzy reasoning approach (FRA).

8.1.3 Application of Fuzzy Reasoning Approach (FRA)

As stated earlier in this report, it may be extremely difficult to conduct probabilistic risk assessment to analyse and estimate the occurrence likelihood of hazards and the magnitudes of their possible consequences because of the uncertainty in the risk data. However, the application of FRA in risk assessment may fill the gap created by other methods due to the following advantages (An, 2007).

(a) the risk can be evaluated directly by using qualitative descriptors;

(b) it is tolerant of imprecise data and ambiguous information;

(c) it gives a more flexible structure for combining qualitative as well as quantitative information.

(d) it focuses on qualitative descriptors in natural language and aims to provide fundamentals for approximate reasoning with imprecise propositions.

Qualitative descriptors are used to represent the condition of risk factor at a given interval. For details of fundamentals of fuzzy reasoning approach (FRA) the reader is referred to Chapter 5. However, it is important to state that the proposed risk assessment model benefits from the combine advantages of concept of design for safety and FRA.

The reason for considering FRA is due to great advantages of enabling effective treatment of data imprecision or approximate information in risk assessment process to produce reliable results. This method deploys;

(a) a membership function (MF) which is regarded as a possibility distribution based on a proposed theory; and

(b) an apparent possibility distribution expressed by fuzzy set theory which is transformed into a possibility measure distribution.

FRA method provides a useful tool for modeling risks and other risk parameters for risk analysis involving the risks with incomplete or redundant safety information (An, 2006). The approach ensures that the contribution of each hazardous event to the overall safety of the offshore platform is taken into consideration in order to represent its relative contribution to the risk level (RL) of the system. This involves the development of fuzzy qualitative descriptors and membership functions (MFs) for describing failure likelihood (FLH), failure consequence severity (FCS), failure consequence probability (FCP) and risk level (RL) expressions, as detailed in Chapter 6.

It is also important to note that definitions of the fuzzy set of RL are generally similar to those described in EN50129, (1998). IEC62278, (2002) BS EN ISO 12100-1 (2003), BS EN ISO 14121-1 (2007) and BS EN ISO 20815 (2008). As detailed in chapter 6, the risk score is defined in such a manner that the lowest score is 0, whereas the highest score is 10. For example, RL qualitative descriptor, 'Minor', is defined on the basis of the risk score ranging from 0 to 3 as shown in Figure 6.5. Similarly, the result of RLs can be expressed either as risk score located in the range from 0 to 10 or as risk category with a belief of percentage as demonstrated in Chapter 6.

8.1.4 Summary on the Knowledge-based Risk Assessment Method (KBRAM)

As mentioned in Chapter 6, the proposed KBRAM comprises of five phases: problem definition phase, data collection and analysis phase, hazard identification phase, risk estimation phase and risk response phase. The process provides a systematic approach to the identification and control of high-risk areas. This framework is considered to be generally applicable to most risk analysis processes of offshore platform but adaptable to different systems with some variation in the process depending on system requirements. The detail discussions on the KBRAM are enumerated in Chapter 6, however, some major highlights are enumerated in the following sections for ease of reference.

Problem definition involves identifying the need for safety, i.e. specific safety requirements. The requirements regarding safety have been specified at different level, e.g. component (hazardous event) level, sub-system (hazard group) level and the overall system (offshore processing unit) level. The following typical items have also been specified in the problem definition phase.

1. Sets of rules and regulation made by the national authorities and classification societies, e.g. Health & Safety Executive, BS Standards, etc.

2. Deterministic requirements for safety, reliability, availability, maintainability, etc.

3. Criteria referring to probability of occurrence of serious hazardous events and the possible consequences.

It is pertinent to note that, KBRAM was specifically designed to effectively process all risk information including uncertainties such as data from oil and gas industry which involves;

(a) operation in a very unique and restrictive environment as is the case with offshore platform;

(b) human error which is considered as a major contributor to possible accidents;

(c) lack of detailed risk information, and

(d) inadequate database provision

Therefore, in such circumstances, a risk analyst may have to describe a given event in vague and imprecise terms such as ‘Tolerable’ and ‘Definite’. Such judgements are obviously subjective and hence the proposed KBRAM has been adequately equipped to support the risks assessment for offshore platform even with the incomplete risk information.

In concluding this section it is believed that, this research work has demonstrated the value of systematic and structured approach deployed in KBRAM to provide a very viable tool for the implementation of safety.

8.2 Conclusions

This work enumerated the concept of design for safety to align with various accidents and incident reports notably the Lord Cullen (1990) which recommended its adoption for offshore facilities development. In the light of this development the current work explores options that could strengthen the concept to deal effectively with the uncertainties in the risk information. In view of this need the proposed model integrated the principles of fuzzy reasoning approach within the concept of design for safety as a way of having a holistic approach developed to deal with the uncertainties in the risk information for the assessment of offshore platform associated risks.

In order to have a broad understanding of the safety need for offshore platform, reviews were conducted on the evolution of safety literature and practices, and the evolution of safety thinking which at the beginning concentrated on technological failures and operator errors. This thinking soon transformed to a more dynamic process progressing to a modest level leading to the development of modern safety theories. Accordingly, this modest improvement facilitated the establishment regulatory agencies like Health & Safety Executives in the UK, OSHA in America thereby promoting the development of safety management system models.

The next step of this report discussed some historical perspectives of safety analysis approaches ranging from earlier tools for identifying hazards and technical risks, to modern tools for assessing failures. Some of the most popular methods used for identifying hazards and assessing risks associated with technical systems have also been reviewed and, their advantages and limitations also enumerated. It was also observed that in certain situations risk assessment need be conducted using a combination of some methods in order to achieve the desired result. However, it was also noted that most of these theories and methods were developed to deal with high-tech industry risk but only a few can be applied effectively in complex design processes with high level of uncertainty such as the offshore installations.

Following observations mentioned above, concepts like design for safety have to be introduced at some stage in order to extend the frontiers of safety management. As mentioned earlier, this concept is found to be suitable for adoption in the current work for the achievement of its aim and objectives of delivering safe offshore platform project. This consideration provided basis for proper alignment of research aim and objectives of achieving a safe design approach as demonstrated through the various part of this report summarised in the subsequent sections of this Chapter. It must also be noted that the need for dealing with uncertainties associated risk information necessitated the search for most suitable methods to be integrated with the concept of design for safety like fuzzy reasoning approach.

Sequel to the above, the fundamentals of fuzzy reasoning approach have been discussed, its advantages enumerated which further reinforced the basis for the development of a combine framework with the concept of design for safety was established. This framework combines the advantages of the concept of design for safety with that of the fuzzy reasoning approach which ensured more effective risk identification and risk estimation. This composite framework was used as the foundation for the development of a new knowledge-based model for the risk assessment for offshore platform. Accordingly, illustrations have also been used all through various sections of this report to demonstrate the procedure of application of the proposed model for assessment of offshore platform associated risks. Specifically the proposed knowledge-based risk assessment method (KBRAM) has also been use to demonstrate the application in a case study scenario.

A case study in Chapter 7 on risk assessment of an offshore processing unit has been conducted to demonstrate how the proposed KBRAM is used to assess the associated risks through a systematic assessment modeling. KBRAM enables experts' experience and knowledge to be processed using some mathematical operations' to compute and generate the necessary inputs required to conduct effective assessment of offshore platform associated risks.

The process illustrated how the application of the various knowledge acquisition techniques could be deployed to develop fuzzy qualitative descriptions and corresponding membership functions (MFs) to qualify risk levels (RLs). This prototype model is tested in the current work through a case study to assess the risks associated with a typical offshore processing unit.

The results obtained using KBRAM are compared with the ones obtained using typical two input parameter fuzzy-based risk assessment method (TPRAM). In the process of this comparison the same industry data was applied through both methods based on same principles of fuzzy reasoning approach with only difference being the additional third input parameter in the case of KBRAM. The final results showed an improved ability by the KBRAM to process data and turn out much more definitive risk levels thereby satisfying the aim of delivering a more cost effective assessment result. This result therefore, demonstrated that the proposed KBRAM has successfully achieved the objectives of this research of facilitating safety decision-making based on cost benefit evaluation of offshore oil and gas platform associated risk.

8.3 Recommendations

This section is intended to highlight the major areas requiring necessary improvements needed to encourage more research activities related to offshore platforms safety decisions. Therefore to achieve safety improvement and cost effective decision making will require stakeholder commitments from early stages of project development. However, it must be noted that this combined requirements can never be fully achieved without some level of research efforts.

Accordingly, the following recommendations are summarised in the section below;

- All major stakeholders must engage in collaborative effort to guaranty all possible risks, their causes and impacts on offshore platforms are effectively identified and properly recorded.

- There must be proper guarantees for researchers to have access to the above mentioned records in order to facilitate safety and decision making.

- Operators are to further establish more acceptable ways of improving management of safety information in conjunction with regulatory bodies and researchers.

- The major stakeholders within the industry and regulatory agencies need to have better collaboration and corporation and come up with programmes design to attract researchers to participate in efforts to achieve a more efficient safety management. These programmes may also involve enforcement agencies to ensure that researchers have some level of unrestricted and timely access to industry safety data for research purposes.

- The operators need to create an enabling environment to guarantee improved data management as well as access to such information for research purposes.

- Risk information still require further efforts by both the operators and regulators in order to achieve harmonise system of recording safety and other related information for the industry. This will be achieved if all the major stakeholders including regulatory agencies must to be involved in kind of joint-partnership for the purpose of establishing necessary programmes specifically for this.

- Researchers require solid support from the industry regulators to guarantee them the right to preserve the independence of their findings.

- Inherent risks still remain major impediments to the safety of offshore oil and gas industry. Therefore, the need to increase efforts towards mitigation of these safety challenges must be accorded high priority and all the major industry stakeholders must remain committed and support these efforts in order to achieve improved safety within the industry.

8.4 Further works

1. The focus in this work is on offshore development project but it will be useful to describe how the model can be applied in the development processes in other industries than offshore, railways etc.

2. To conduct investigation for other method which has the ability to deal with uncertainties associated with expert judgements

3. To continue further efforts of fine tuning the fuzzy reasoning approach based methods in order to improve its acceptability

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Appendix A

Questionnaire used

for

Collection

of

Experts' Judgements

OFFSHORE PLATFORMS: FAILURE DATA UNCERTAINTY MANAGEMENT QUERSTIONNAIRE

My name is Abubakar Umar and I am currently in 3rd year of my PhD studying in school of Engineering at the University of Birmingham. My research project is “Design Safety for Offshore Oil & Gas Platforms”.

Offshore oil and gas installation is associated with several inherent risks which could result in loss of lives, degradation of the environment, and damage to property or capital assets. However **fire and explosion** have been rated as the top two risks. Failures of the processing system equipments such as ***Separators, Compressors, Flash drums and Driers*** are generally believed to be associated with this.

This questionnaire is designed to collect information on failure consequence severity and failure consequence probability for the above listed equipments to help in suggesting safety improvements. Your help and time is greatly appreciated and extremely useful.

The questionnaire is simple to complete and is totally confidential, the results will be summarised in my PhD thesis as such individual questionnaires will not be shown. It can be completed electronically by clicking in the box (es) under the relevant to score (s). If you are completing the Questionnaire manually you can also mark (**X**) as appropriate. It should not take more than 10 minutes to complete.

Many thanks.

1. Failure consequence severity (FCS)

Failure consequence severity describes the magnitude of possible consequences of failure event.

Please use this scale to allocate score

1 10
Negligible Catastrophic

If you cannot give a definite number, you can provide a range, for example, by ticking two or three numbers.

Separator 1											
S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Flow control valve	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2	Leak indicator failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3	Excess flow at upstream	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4	Impurities causing exothermic reaction	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5	Sudden change in pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7	High pressure upstream line	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8	Upstream pressure controller failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	Condensate line choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10	Oil pipeline or valve choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11	Gas pipeline or valve choke	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12	Safety valve undersize	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13	Safety/pressure valve choked or could not function on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14	External heating	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
15	Exothermic reaction in vessel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
16	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
17	Pressure controller system of separator failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
18	Pressure or safety release failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
19	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
20	Ignition due to heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
21	Electric spark as source of ignition	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Separator 2											
S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Leak from joints										
2	Leak from main pipeline										
3	Leak from joints										
4	Leak from main pipeline										
5	Leak from vessel										
6	Leak from fracture, joints or crack										
7	Leak from the pipe connection										
8	Leak from safety valve										
9	Leak from pressure release valve										
10	Leak from control valves										
11	Outlet pipe choked										
12	High pressure upstream line										
13	Sudden phase change										
14	External heat absorption causing increase in pressure										
15	Ignition due to explosion energy										
16	Ignition due to external heat from surrounding										
17	Ignition due to electric spark										
18	Release from pipe after explosion										
19	Release from vessel aftermath of explosion										
20	Ignition due to external explosion energy										
21	Ignition due to fire heat load										

Compressors											
	Element	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Leak from compressor downstream pipeline										
2	Leak from compressor downstream pipeline joints										
3	Leak from compressor upstream pipeline										
4	Leak from joints of compressor upstream pipeline										
5	Release from casing of compressor										
6	Leaking of seal										
7	Release from impeller										
8	Compressor completely failed causing release of chemical										
9	Leak from junction of pump and pipeline										
10	Leak from rotor										
11	Pump failed to operate and caused release of chemical										
12	Leak from casing										
13	Ignition due to explosion energy										
14	Ignition due to external heat from surrounding										

15	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
16	Fire caused by failure of pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
17	Fire caused vessel to fail and release of chemical from vessel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Flash drum

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Leak from upstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2	Leak from upstream pipeline joints	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3	High-pressure in vessel causing rupture of vessel and release of gas	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4	Leak from joints or flange	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5	Leak from downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6	Leak from joints of downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7	Leak from joint of gas pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8	Leak from gas pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14	VCE causes pipeline to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
15	VCE causes vessel to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Drier

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Impurities in feed line	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2	Control system failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3	Sudden phase change	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5	Heating due to external heat source	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6	Drier outlet line choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7	Outlet valve choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8	Safety valve failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	Pressure relief failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14	BLEVE causes vessel to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

15	BLEVE causes pipeline to fail and release chemical	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

2. Failure consequence probability (FCP)

Failure consequence probability is defined as probability that effects will happen given the occurrence of the failure**.**

Please use this scale to allocate score

1 **10**
Highly unlikely **Definite**

If you cannot give a definite number, you can provide a range, for example, by ticking two or three numbers.

Separator 1											
S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Flow control valve	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2	Leak indicator failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3	Excess flow at upstream	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4	Impurities causing exothermic reaction	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5	Sudden change in pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7	High pressure upstream line	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8	Upstream pressure controller failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	Condensate line choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10	Oil pipeline or valve choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11	Gas pipeline or valve choke	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12	Safety valve undersize	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13	Safety/pressure valve choked or could not function on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14	External heating	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
15	Exothermic reaction in vessel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
16	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
17	Pressure controller system of separator failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
18	Pressure or safety release failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
19	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
20	Ignition due to heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
21	Electric spark as source of ignition	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Separator 2											
S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Leak from joints	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2	Leak from main pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3	Leak from joints	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4	Leak from main pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5	Leak from vessel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6	Leak from fracture, joints or crack	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7	Leak from the pipe connection	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8	Leak from safety valve	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	Leak from pressure release valve	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10	Leak from control valves	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11	Outlet pipe choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12	High pressure upstream line	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13	Sudden phase change	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14	External heat absorption causing increase in pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
15	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
16	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
17	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
18	Release from pipe after explosion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
19	Release from vessel aftermath of explosion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
20	Ignition due to external explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
21	Ignition due to fire heat load	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Compressors											
	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Leak from compressor downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2	Leak from compressor downstream pipeline joints	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3	Leak from compressor upstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4	Leak from joints of compressor upstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5	Release from casing of compressor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6	Leaking of seal	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7	Release from impeller	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8	Compressor completely failed causing release of chemical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	Leak from junction of pump and pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10	Leak from rotor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11	Pump failed to operate and caused release of chemical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12	Leak from casing	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14	Ignition due to external heat from										

	surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
15	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
16	Fire caused by failure of pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
17	Fire caused vessel to fail and release of chemical from vessel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Flash drum

S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Leak from upstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2	Leak from upstream pipeline joints	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3	High-pressure in vessel causing rupture of vessel and release of gas	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4	Leak from joints or flange	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5	Leak from downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6	Leak from joints of downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7	Leak from joint of gas pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8	Leak from gas pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14	VCE causes pipeline to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
15	VCE causes vessel to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Drier

S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Impurities in feed line	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
2	Control system failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
3	Sudden phase change	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
4	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
5	Heating due to external heat source	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
6	Drier outlet line choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
7	Outlet valve choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
8	Safety valve failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
9	Pressure relief failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
10	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
11	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
12	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
13	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
14	BLEVE causes vessel to fail and release										

	chemical	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐
15	BLEVE causes pipeline to fail and release chemical	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐

THANK YOU VERY MUCH FOR TAKING TIME TO COMPLETE THIS QUESTIONNAIRE, YOUR HELP IS HIGHLY APPRECIATED.

Appendix B

Sample of completed

Questionnaire

Sample 1

Response From Expert E-1

OFFSHORE PLATFORMS: FAILURE DATA UNCERTAINTY MANAGEMENT QUERSTIONNAIRE

My name is Abubakar Umar and I am currently in 3rd year of my PhD studying in school of Engineering at the University of Birmingham. My research project is “Safety for management in the design of offshore platforms”.

Offshore oil and gas installation is associated with several inherent risks which could result in loss of lives, degradation of the environment, and damage to property or capital assets. However **fire and explosion** have been rated as the top two risks. Failures of the processing system equipments such as ***Separators, Compressors, Flash drums and Driers*** are generally believed to be associated with this.

This questionnaire is designed to collect information on failure consequence severity and failure consequence probability for the above listed equipments to help in suggesting safety improvements. Your help and time is greatly appreciated and extremely useful.

The questionnaire is simple to complete and is totally confidential, the results will be summarised in my PhD thesis as such individual questionnaires will not be shown. It can be completed electronically by clicking in the box (es) under the relevant to score (s). If you are completing the Questionnaire manually you can also mark (**X**) as appropriate. It should not take more than 10 minutes to complete.

Many thanks.

1. Failure consequence severity

Failure consequence severity describes the magnitude of possible consequences of failure event.

Please use this scale to allocate score

1 2 3 4 5 6 7 8 9 10
Negligible Extreme

If you cannot give a definite number, you can provide a range, for example, by ticking two or three numbers.

Separator 1											
S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Flow control valve	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
2	Leak indicator failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
3	Excess flow at upstream	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
4	Impurities causing exothermic reaction	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
5	Sudden change in pressure	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
6	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
7	High pressure upstream line	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
8	Upstream pressure controller failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
9	Condensate line choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
10	Oil pipeline or valve choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
11	Gas pipeline or valve choke	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
12	Safety valve undersize	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
13	Safety/pressure valve choked or could not function on demand	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
14	External heating	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
15	Exothermic reaction in vessel	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
16	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
17	Pressure controller system of separator failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
18	Pressure or safety release failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
19	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
20	Ignition due to heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
21	Electric spark as source of ignition	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

Separator 2

S/No	Element	Score 1	2	3	4	5	6	7	8	9	10
1	Leak from joints	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
2	Leak from main pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
3	Leak from joints	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
4	Leak from main pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
5	Leak from vessel	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
6	Leak from fracture, joints or crack	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
7	Leak from the pipe connection	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
8	Leak from safety valve	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
9	Leak from pressure release valve	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
10	Leak from control valves	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
11	Outlet pipe choked	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
12	High pressure upstream line	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
13	Sudden phase change	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
14	External heat absorption causing increase in pressure	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
15	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
16	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
17	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
18	Release from pipe after explosion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
19	Release from vessel aftermath of explosion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
20	Ignition due to external explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
21	Ignition due to fire heat load	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

Compressors

	Element	Score 1	2	3	4	5	6	7	8	9	10
1	Leak from compressor downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
2	Leak from compressor downstream pipeline joints	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
3	Leak from compressor upstream pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
4	Leak from joints of compressor upstream pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
5	Release from casing of compressor	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
6	Leaking of seal	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
7	Release from impeller	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
8	Compressor completely failed causing release of chemical	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
9	Leak from junction of pump and pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
10	Leak from rotor	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
11	Pump failed to operate and caused release of chemical	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
12	Leak from casing	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
13	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
14	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

15	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
16	Fire caused by failure of pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
17	Fire caused vessel to fail and release of chemical from vessel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

Flash drum

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Leak from upstream pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
2	Leak from upstream pipeline joints	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
3	High-pressure in vessel causing rupture of vessel and release of gas	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
4	Leak from joints or flange	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
5	Leak from downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
6	Leak from joints of downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
7	Leak from joint of gas pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
8	Leak from gas pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
9	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
10	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
11	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
12	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
13	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
14	VCE causes pipeline to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
15	VCE causes vessel to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐

Drier

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Impurities in feed line	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
2	Control system failed	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
3	Sudden phase change	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
4	Temperature controller failed	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
5	Heating due to external heat source	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
6	Drier outlet line choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
7	Outlet valve choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
8	Safety valve failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
9	Pressure relief failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
10	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
11	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
12	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
13	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

14	BLEVE causes vessel to fail and release chemical	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☒
15	BLEVE causes pipeline to fail and release chemical	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☒

2. Failure consequence probability

Failure consequence probability is defined as probability that effects will happen given the occurrence of the failure**.**

Please use this scale to allocate score

1 2 3 4 5 6 7 8 9 10
Highly unlikely Definite

If you cannot give a definite number, you can provide a range, for example, by ticking two or three numbers.

Separator 1											
S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Flow control valve	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
2	Leak indicator failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
3	Excess flow at upstream	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
4	Impurities causing exothermic reaction	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
5	Sudden change in pressure	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
6	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
7	High pressure upstream line	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
8	Upstream pressure controller failed	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
9	Condensate line choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
10	Oil pipeline or valve choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
11	Gas pipeline or valve choke	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
12	Safety valve undersize	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
13	Safety/pressure valve choked or could not function on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
14	External heating	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
15	Exothermic reaction in vessel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
16	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
17	Pressure controller system of separator failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
18	Pressure or safety release failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
19	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
20	Ignition due to heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
21	Electric spark as source of ignition	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

Separator 2

S/No	Element	1	2	3	4	5	6	7	8	9	10
1	Leak from joints	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
2	Leak from main pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
3	Leak from joints	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
4	Leak from main pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
5	Leak from vessel	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
6	Leak from fracture, joints or crack	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
7	Leak from the pipe connection	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
8	Leak from safety valve	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
9	Leak from pressure release valve	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
10	Leak from control valves	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
11	Outlet pipe choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
12	High pressure upstream line	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
13	Sudden phase change	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
14	External heat absorption causing increase in pressure	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
15	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
16	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
17	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
18	Release from pipe after explosion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
19	Release from vessel aftermath of explosion	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
20	Ignition due to external explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
21	Ignition due to fire heat load	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

Compressors

	Element	1	2	3	4	5	6	7	8	9	10
1	Leak from compressor downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
2	Leak from compressor downstream pipeline joints	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
3	Leak from compressor upstream pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
4	Leak from joints of compressor upstream pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
5	Release from casing of compressor	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
6	Leaking of seal	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
7	Release from impeller	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
8	Compressor completely failed causing release of chemical	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
9	Leak from junction of pump and pipeline	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
10	Leak from rotor	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
11	Pump failed to operate and caused release of chemical	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
12	Leak from casing	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
13	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
14	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

S/No	Element	1	2	3	4	5	6	7	8	9	10
15	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
16	Fire caused by failure of pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
17	Fire caused vessel to fail and release of chemical from vessel	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

Flash drum

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Leak from upstream pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
2	Leak from upstream pipeline joints	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
3	High-pressure in vessel causing rupture of vessel and release of gas	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
4	Leak from joints or flange	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
5	Leak from downstream pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
6	Leak from joints of downstream pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
7	Leak from joint of gas pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
8	Leak from gas pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
9	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
10	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
11	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
12	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
13	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
14	VCE causes pipeline to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
15	VCE causes vessel to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐

Drier

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Impurities in feed line	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
2	Control system failed	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
3	Sudden phase change	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
4	Temperature controller failed	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
5	Heating due to external heat source	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
6	Drier outlet line choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
7	Outlet valve choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
8	Safety valve failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
9	Pressure relief failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
10	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
11	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
12	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
13	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
14	BLEVE causes vessel to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

15	BLEVE causes pipeline to fail and release chemical	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☒

THANK YOU VERY MUCH FOR TAKING TIME TO COMPLETE THIS QUESTIONNAIRE, YOUR HELP IS HIGHLY APPRECIATED.

Sample 2

Response from Experts E-2

OFFSHORE PLATFORMS: FAILURE DATA UNCERTAINTY MANAGEMENT QUERSTIONNAIRE

My name is Abubakar Umar and I am currently in 3rd year of my PhD studying in school of Engineering at the University of Birmingham. My research project is "Safety for management in the design of offshore platforms".

Offshore oil and gas installation is associated with several inherent risks which could result in loss of lives, degradation of the environment, and damage to property or capital assets. However **fire and explosion** have been rated as the top two risks. Failures of the processing system equipments such as ***Separators, Compressors, Flash drums and Driers*** are generally believed to be associated with this.

This questionnaire is designed to collect information on failure consequence severity and failure consequence probability for the above listed equipments to help in suggesting safety improvements. Your help and time is greatly appreciated and extremely useful.

The questionnaire is simple to complete and is totally confidential, the results will be summarised in my PhD thesis as such individual questionnaires will not be shown. It can be completed electronically by clicking in the box (es) under the relevant to score (s). If you are completing the Questionnaire manually you can also mark (**X**) as appropriate. It should not take more than 10 minutes to complete.

Many thanks.

1. Failure consequence severity

Failure consequence severity describes the magnitude of possible consequences of failure event.

Please use this scale to allocate score

1 2 3 4 5 6 7 8 9 10
Negligible Extreme

If you cannot give a definite number, you can provide a range, for example, by ticking two or three numbers.

Separator 1											
S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Flow control valve	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
2	Leak indicator failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
3	Excess flow at upstream	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
4	Impurities causing exothermic reaction	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
5	Sudden change in pressure	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
6	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
7	High pressure upstream line	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
8	Upstream pressure controller failed	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
9	Condensate line choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
10	Oil pipeline or valve choked	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
11	Gas pipeline or valve choke	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
12	Safety valve undersize	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
13	Safety/pressure valve choked or could not function on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
14	External heating	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
15	Exothermic reaction in vessel	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
16	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
17	Pressure controller system of separator failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
18	Pressure or safety release failed	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
19	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
20	Ignition due to heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
21	Electric spark as source of ignition	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

Separator 2											
S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Leak from joints	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
2	Leak from main pipeline	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
3	Leak from joints	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
4	Leak from main pipeline	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
5	Leak from vessel	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
6	Leak from fracture, joints or crack	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
7	Leak from the pipe connection	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
8	Leak from safety valve	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
9	Leak from pressure release valve	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
10	Leak from control valves	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
11	Outlet pipe choked	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
12	High pressure upstream line	☐	☐	☐	☐	☒	☐	☐	☐	☐	☐
13	Sudden phase change	☐	☐	☐	☐	☒	☐	☐	☐	☐	☐
14	External heat absorption causing increase in pressure	☐	☐	☐	☐	☒	☐	☐	☐	☐	☐
15	Ignition due to explosion energy	☐	☐	☐	☐	☒	☐	☐	☐	☐	☐
16	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
17	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
18	Release from pipe after explosion	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
19	Release from vessel aftermath of explosion	☐	☐	☐	☐	☐	☐	☐	☐	☒	☐
20	Ignition due to external explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
21	Ignition due to fire heat load	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐

Compressors											
	Element	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Leak from compressor downstream pipeline	☐	☐	☐	☐	☐	☐	☐	☐	☒	☐
2	Leak from compressor downstream pipeline joints	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
3	Leak from compressor upstream pipeline	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
4	Leak from joints of compressor upstream pipeline	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
5	Release from casing of compressor	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
6	Leaking of seal	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
7	Release from impeller	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
8	Compressor completely failed causing release of chemical	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
9	Leak from junction of pump and pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
10	Leak from rotor	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
11	Pump failed to operate and caused release of chemical	☐	☐	☐	☒	☐	☐	☐	☒	☐	☐
12	Leak from casing	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
13	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
14	Ignition due to external heat from surrounding	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐

		1	2	3	4	5	6	7	8	9	10
15	Ignition due to electric spark								X		
16	Fire caused by failure of pipeline					X					
17	Fire caused vessel to fail and release of chemical from vessel								X		

Flash drum

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Leak from upstream pipeline				X						
2	Leak from upstream pipeline joints				X						
3	High-pressure in vessel causing rupture of vessel and release of gas								X		
4	Leak from joints or flange						X				
5	Leak from downstream pipeline				X						
6	Leak from joints of downstream pipeline				X						
7	Leak from joint of gas pipeline				X						
8	Leak from gas pipeline				X						
9	Ignition due to explosion energy								X		
10	Ignition due to external heat from surrounding								X		
11	Ignition due to electric spark								X		
12	Ignition due to explosion energy								X		
13	Ignition due to external heat from surrounding								X		
14	VCE causes pipeline to fail and release chemical				X						
15	VCE causes vessel to fail and release chemical				X						

Drier

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Impurities in feed line				X						
2	Control system failed						X				
3	Sudden phase change						X				
4	Temperature controller failed						X				
5	Heating due to external heat source						X				
6	Drier outlet line choked								X		
7	Outlet valve choked								X		
8	Safety valve failed to operate on demand						X				
9	Pressure relief failed to operate on demand								X		
10	Ignition due to external heat from surroundings						X				
11	Ignition due to electric spark						X				
12	Ignition due to explosion energy						X				
13	Ignition due to external heat from surroundings						X				
14	BLEVE causes vessel to fail and release chemical						X				

15	BLEVE causes pipeline to fail and release chemical	☐ ☐ ☐ ☐ ☐ ☒ ☐ ☐ ☐ ☐

2. Failure consequence probability

Failure consequence probability is defined as probability that effects will happen given the occurrence of the failure**.**

Please use this scale to allocate score

1 2 3 4 5 6 7 8 9 10
Highly unlikely Definite

If you cannot give a definite number, you can provide a range, for example, by ticking two or three numbers.

Separator 1											
S/No	**Element**	**Score**									
		1	2	3	4	5	6	7	8	9	10
1	Flow control valve	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
2	Leak indicator failed	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
3	Excess flow at upstream	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
4	Impurities causing exothermic reaction	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
5	Sudden change in pressure	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
6	Temperature controller failed	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
7	High pressure upstream line	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
8	Upstream pressure controller failed	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
9	Condensate line choked	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
10	Oil pipeline or valve choked	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
11	Gas pipeline or valve choke	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
12	Safety valve undersize	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
13	Safety/pressure valve choked or could not function on demand	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
14	External heating	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
15	Exothermic reaction in vessel	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
16	Temperature controller failed	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
17	Pressure controller system of separator failed	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
18	Pressure or safety release failed	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
19	Ignition due to explosion energy	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
20	Ignition due to heat from surrounding	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
21	Electric spark as source of ignition	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐

Separator 2

S/No	Element	Score 1	2	3	4	5	6	7	8	9	10
1	Leak from joints	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
2	Leak from main pipeline	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
3	Leak from joints	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
4	Leak from main pipeline	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
5	Leak from vessel	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
6	Leak from fracture, joints or crack	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
7	Leak from the pipe connection	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
8	Leak from safety valve	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
9	Leak from pressure release valve	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
10	Leak from control valves	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
11	Outlet pipe choked	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
12	High pressure upstream line	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
13	Sudden phase change	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
14	External heat absorption causing increase in pressure	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
15	Ignition due to explosion energy	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
16	Ignition due to external heat from surrounding	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
17	Ignition due to electric spark	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
18	Release from pipe after explosion	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
19	Release from vessel aftermath of explosion	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
20	Ignition due to external explosion energy	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
21	Ignition due to fire heat load	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐

Compressors

	Element	Score 1	2	3	4	5	6	7	8	9	10
1	Leak from compressor downstream pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
2	Leak from compressor downstream pipeline joints	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
3	Leak from compressor upstream pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
4	Leak from joints of compressor upstream pipeline	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
5	Release from casing of compressor	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
6	Leaking of seal	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
7	Release from impeller	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
8	Compressor completely failed causing release of chemical	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
9	Leak from junction of pump and pipeline	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
10	Leak from rotor	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
11	Pump failed to operate and caused release of chemical	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
12	Leak from casing	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
13	Ignition due to explosion energy	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
14	Ignition due to external heat from surrounding	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐

S/No	Element	1	2	3	4	5	6	7	8	9	10
15	Ignition due to electric spark	☐	☒	☐	☐	☐	☐	☐	☐	☐	☐
16	Fire caused by failure of pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
17	Fire caused vessel to fail and release of chemical from vessel	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐

Flash drum

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Leak from upstream pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
2	Leak from upstream pipeline joints	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
3	High-pressure in vessel causing rupture of vessel and release of gas	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
4	Leak from joints or flange	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
5	Leak from downstream pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
6	Leak from joints of downstream pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
7	Leak from joint of gas pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
8	Leak from gas pipeline	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
9	Ignition due to explosion energy	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
10	Ignition due to external heat from surrounding	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
11	Ignition due to electric spark	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
12	Ignition due to explosion energy	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
13	Ignition due to external heat from surrounding	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
14	VCE causes pipeline to fail and release chemical	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
15	VCE causes vessel to fail and release chemical	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐

Drier

S/No	Element	Score									
		1	2	3	4	5	6	7	8	9	10
1	Impurities in feed line	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
2	Control system failed	☐	☐	☐	☒	☐	☐	☐	☐	☐	☐
3	Sudden phase change	☐	☐	☐	☐	☐	☒	☐	☐	☐	☐
4	Temperature controller failed	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
5	Heating due to external heat source	☐	☐	☐	☐	☐	☐	☐	☒	☐	☐
6	Drier outlet line choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
7	Outlet valve choked	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
8	Safety valve failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
9	Pressure relief failed to operate on demand	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
10	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
11	Ignition due to electric spark	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
12	Ignition due to explosion energy	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
13	Ignition due to external heat from surroundings	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒
14	BLEVE causes vessel to fail and release chemical	☐	☐	☐	☐	☐	☐	☐	☐	☐	☒

15	BLEVE causes pipeline to fail and release chemical	☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☐ ☒

THANK YOU VERY MUCH FOR TAKING TIME TO COMPLETE THIS QUESTIONNAIRE, YOUR HELP IS HIGHLY APPRECIATED.

Appendix 3

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Application of principles of inherently safe design methodology into the development of offshore platforms

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ABSTRACT: Offshore platform installation is associated with several inherent risks arising from major critical safety challenges such as fires, explosions, blowouts, falling objects, earthquake, extreme weather, and impact from moving objects such as helicopters or ships. These critical problems are due largely to design errors or inadequacies, and poor maintenance. The safety challenges highlighted above could result in loss of lives, degradation of the environment, and damage to property or capital assets.

The traditional safe design concept for an offshore platform is based mainly on provision of redundant levels of prevention barriers and other mitigation systems which themselves may introduce additional hazards. The concept of "design for safety" to be deployed is to investigate critical risks on the offshore platforms which require proper attention in the design process, in particular, at the early design stages. The concept envisaged in this paper is to utilise the proactive approach aimed at avoiding or minimising the need to incorporate extensive safety systems for the control and mitigation of hazards. This approach involves the enlargement of the design team to accommodate wider participation of both the designers and operation personnel to help create more opportunities aimed at achieving reduction in the hazard likelihood, severity and consequences at the early stages of the design. In conclusion this paper seeks to highlight the problems in the design process with a view to address critical hazards of fire and explosion on offshore platforms.

1 INTRODUCTION

Offshore oil and gas platform main features can usually be divided into a number of operational modules such as water injection, high-compression, sea water de-aeration and other modules include local power and main electrical rooms and an accommodation blocks. These operational areas are most often crowded by or congested with various obstacles such as pipelines and other operational safety equipments.

The platforms have high standard of inherent risks associated with the design errors in the offshore development projects that necessitates the need for continuous work in the areas of managing such risks. These inherent risks sometimes result in loss of live to people, degrade the environment and or damage to the property or economic assets. The safety management approach in this context is to establish appropriate risk elimination or reduction measures through design. This approach will require detailed hazard identification and risk assessment of errors at various stages (Raftery, 1993).

The Danish Energy Department (DEA, 2006) and UK Health and Safety Executive (HSE, 2005) review safety guidelines based on the performance of offshore oil & gas industry over the years which indicate that about 80% of the risks to personnel are related to the process and structural failures. The most critical risks offshore include blowouts, fires, explosions, collision with moving objects (e.g. Vessels), falling objects, extreme weather condition and earthquakes. It is essential that review of some major accidents such as Piper Alpha, Bhopal and Phillips accidents revealed that most of the accidents are process related and the consequences could be minimized if proper considerations is given to details during the design process.

2 A REVIEW OF CONTEMPORARY PRACTICES

2.1 *Offshore platform development phases*

This section is intended to highlight the hazards associated with the various development phases of an offshore platform project with a view to incorporating safety features through the design from inception. This process is usually referred to as “design for safety”.

An offshore project development may be classified into three broad stages of design, construction and operation (Pappas, 1994). These stages can be further divided into a sequence including, for instance, planning/feasibility design phase, conceptual design phase, pre-engineering phase, detailed engineering phase, construction phase, commissioning and start up phase. However, a design of an offshore platform at the early stage usually involves planning/feasibility phase and conceptual phase. The level of insufficiency of data and high level uncertainty associated with offshore installation may not allow the use of traditional methods early enough to enable safety decision making. In this case, the research activities will therefore focus on the integration of safety features through design process at the early stage i.e. planning/feasibility and conceptual studies.

2.1.1 *Planning/feasibility phase*

The objective of the studies in the planning/feasibility design phase is to evaluate whether or not further development of a field is technically feasible and commercially favourable. The safety evaluation within this phase usually plays a relatively subordinate role regarding whether to develop a field or not. Therefore, the risk estimation will be aimed at comparing different factors with respect to safety. The results should therefore be given as a ranking of the alternatives rather than to estimate absolute levels of risk. Safe design usually consists of i) identification of relevant hazards, ii) estimation of the probability of each accident, and iii) estimation of the possible consequences.

Estimation of probabilities and consequences should be used in order to compare different types of fields and offshore platform design. In general, safe design in the planning/feasibility design phase is aimed at specifying one or more design alternatives for offshore platforms (An, et al, 2000a & b).

As described earlier on this paper, at this stage, safety information or data is not sufficient for the performance of extensive risk evaluation. Therefore, assumptions have to be made so that an offshore platform may be designed in accordance with standard requirements and acceptance criteria. However, the risks associated with an offshore platform which are residual in nature, can be considered for preliminary evaluation while the design basis risks would be dealt with in the subsequent design phases using comprehensive design methods based on accidental specifications (Pappas, 1994).

Feasibility risk evaluation is mainly devoted to comparison of different platform alternatives thereby reducing the importance of significant uncertainties. It was suggested that, quantitative comparison rather than qualitative one will provide more reliable input into the decision making process (Uher & Toakley, 1999).

2.1.2 *Conceptual study phase*

The objective of conceptual design phase is to provide safety-related input in the process of developing and selecting an offshore platform. The conceptual design shall satisfy both the operator, and regulatory and company’s requirements for a safe and economically attractive solution. The acceptability of the design concept shall be documented through evaluation of safety case that will accompany the field development plan. The major activities in this phase are confirmation of the recommendations in the previous phase and decision making on platform installation based on commercial, technical and other considerations relevant to such a project as well as definition of the main features of the selected field.

As stated above, the main objective of this phase is concerned with the definition of commercial viability of the project and optimisation of the entire installation. However, from the point of view of safety, other aspects are also considered to be of significant importance in the decision process including orientation, overall layout, support structure, transport system, riser locations, drilling and production schedules and so on. The hazards associated with the platform such as fires, explosions, ship and helicopter collisions, environmental damage and falling objects can be used to conduct some level of risk analyses.

It should be noted that platform design has not commenced at this stage and therefore, the computation of system reliability will not be possible, but consequence analysis dealing with the fire and explosions can be performed with some level of precision (Vinnem & Hope, 1986). It is therefore, desirable to conduct some level of quantitative risk analyses at this stage in order to synchronise the activities with the subsequent phases where quantitative data will be more available. It was suggested that the safety requirements should be defined through risk assessment based on functional needs rather than specific design details.

2.1.3 *Detailed design phase*

This phase starts following the decision on all conceptual design aspects of the platform, which is concern with detailed specification required for fixing all engineering system and equipments. The main objective at this stage is to produce engineering details needed for the fabrication, construction, installation and commissioning for platform operation. It is also important to ensure that safety recommendations produced at the concept phase are incorporated into the activities in this phase in order to ascertain that all necessary safety precautions are taken with regard to start -up and operation. There is therefore, the need at this stage to conduct some level of risk analysis as it is still possible to modify the design details.

Hazard and Operability Analysis (HAZOP) can be conducted at this early stage of engineering phase to:

a) evaluate the design process in details regarding drilling and support system,
b) provide input for the detailed hazard identification for final risk analysis.

The risk analysis to be performed will serve as a basis for the compilation of all information or data required for:

- identification of all possible risk reduction measures,
- identification of platform risk level,
- analysis of future platform extensions,
- analysis of future platform modifications,
- Design of future platforms.

To achieve the above, all necessary conditions for risk analysis including that uncertainty estimations and assumptions must be clearly provided.

2.2 *A Review of the design for safety methodology*

"Design for safety" is a process of minimising injury or death of personnel, damages to offshore products and pollution to the environment (Lois, P. et al 2002). It involves a concept of incorporating safety into the design process from the early stages, which is achieved through a systematic approach to the identification and control of high -risk areas.

The constraints associated with the "design for safety" process need to be highlighted in order to achieve the desired integration. The constraints or difficulties associated with "design for safety" include the problems of getting sufficient data, effect of multiple factors or processes, complicated decision making process etc (Wang, 1996; An, et al. 2000a & b).

The development of safety model through the design of such a structure like offshore platform can be difficult and will thus require approximations and judgements of operative with the thorough knowledge of the operation of the installation (How, et al 2001; Wang & Ruxton, 1998). This may require application of safety analysis methods either individually or in combination to conduct a qualitative or a quantitative safety analysis. The problem with application of these methods is a lack of specification of where and how to apply them or how they interrelate. Application of these methods will therefore require good knowledge of qualitative and quantitative analysis techniques.

2.3 *Principles of inherently safe design*

An inherently safe approach to fire and explosion hazard management involves application of measures to avoid or eliminate hazards or reduce their magnitude, severity, or likelihood of occurrence by careful attention to the fundamental design or layout. General notion of inherent safety is delivering normally unattended installations (NUI) and pipeline that does not leak, collapse or sink and has no one on it to be killed over the life of the facility. Both operators and designers are to be engaged in a single team with the former group assisting in the design process. The inherently safe design was first introduced 1976 following the Flixborough accident in 1974. It was used to refine the concept and practice in subsequent publications. These principles include minimisation (or intensification), substitution, moderation (or attenuation) and simplification. Inherently safe design does not guarantee absolute safety but compared to inherently unsafe design where problems are likely to escalate more catastrophically case such as Piper Alpha and Bhopal disasters that provide the best examples of inherently unsafe designs.

In offshore development, the associated risks can never be completely eliminated, but some degree of inherent safety can be achieved through the various phases of design. The residual risk elements are considered for preliminary evaluation at the feasibility study phase while design based risks are to be dealt with in the subsequent design phases.

Risk evaluation performed at feasibility design stage is concern with the comparison of different platform alternatives in order to reduce the significant uncertainties.

The design optimization involves the process of selection of various alternatives in attempt to reduce the risks to ‘As Low As Reasonably Practicable’ (ALARP). This process involves elimination of the provision of redundant levels of prevention barriers and other mitigation systems, which themselves may contribute to additional risk problems. The process will however, require the identification and assessment of major risk contributors which could be achieved early in the project by the use of quantitative risk assessment techniques.

Identification of major risks by engineering judgement will not achieve the desired result if a structured approach is not adopted at the early stages thereby necessitating the use of costly remedial measure rather than the desired loss prevention (Vinnem & Hope, 1998). However, the general principles of inherently safe design approach as applied in the process industry can be employed in the offshore domain, which are described as below:
a) Minimisation/intensification is the process of elimination or reduction in the large inventory of raw materials, intermediate products and/or reduction in the volume of equipment or storage facilities.

b) Substitution is the process of substituting hazardous substances with the less hazardous ones.
c) Simplification is to simplify parts of the complex plant design and revise ambiguous operating instructions to reduce wrong actions.
d) Limitation is to produce hazardous substances at different sites to eliminate transportation of such material within one site and reduce inventory reactors at such place by:

- Moving the building to a greater distance away from hazardous production facilities.
- Build a dyke to contain the released materials due to loss of primary containment
- Making use of the magnetically coupled pumps where possible to eliminate leaks from seals.
- Mounting the LPG tanks to minimize the consequences of BLEVE (Boiling Liquid Expanding Vapour Explosion).

The offshore industry is one of the few that made extensive use of inherently safe design through the adoption of some of the principles and related specifics. Gupta *et al* (2002) observed that offshore industry leads others in targeting hazards using the concept of inherently safe design. In the offshore oil and gas industry the application of principle of inherently safe design has been achieved through:

a) The use of intensification to simplify the production process and plant design.
b) Simplifying overall layout to reduce the hazards associated with complex setting.
c) Isolating highly hazardous materials where possible.
d) Moderating high pressure and temperature through changes in the process chemistry and/or catalyst.
e) Reducing the number of valves and small connection for instrument.
f) Involving operators at the early stage of the design process in order to obtain proper insight into the common errors associated with the operations that need to be targeted for control or elimination.

In recent years, design engineers and safety researchers have continued to develop and apply various safety techniques for identification of all potential hazardous events, and respective causes and possible consequences. The various traditional safety analysis methods can be incorporated into the design process either individually or in combination to identify the potential risks associated with the system, and these safety analysis methods include:

- Preliminary hazard analysis (PHA),
- Fault tree analysis (FTA),
- Event tree analysis (ETA),
- Failure mode, effects and criticality analysis (FMECA),
- Cause consequence analysis (CCA),
- Hazard and operability method (HAZOP),
- Boolean representation method (BRM),
- Simulation analysis.

However, these techniques employ top-down and bottom-up safety assessment approaches.

2.4 *Top-down safety assessment approach*

A typical top-down process starts with the identification of the top events which can be obtained from previous accident and incident reports of similar systems. Once the top events required to be studied further are determined, the causes leading to them can be identified deductively with increasing detail until all the causes are identified at the required level of resolution. Either qualitative or quantitative analysis can be carried out to estimate and evaluate risks. A Design review can then be conducted through further processing the information obtained.
For offshore engineering systems with comparatively simple layout design, the top-down approach may prove convenient and efficient as it only deals with the failure path leading to the top events. It is obvious that the experience and good understanding of the engineering system is very

important for the efficient application of this method.

However, offshore system with a complicated layout, there may be a lack in the knowledge or experience regarding the design solution and its possible effects on system safety. For such systems, the top -down approach may have the following problems:

- Failure data may not be available from previous accidents and incident reports of similar systems.
- There may be uncertainties about the identification of all failure causes associated with the top events.
- Deductive characteristics in a top-down safety assessment process may not address the complex interaction present in a complex system in a rigorous way.

2.5 *Bottom-up safety assessment approach*

In this approach, an offshore system may be divided into subsystems which can be further broken down into the constituent parts or component level in order to identify all possible hazards. The hazard identification can be initiated from the component level, then progress up to the subsystem level and finally to the system level. The combinations of all possible failure events at both the component and the subsystem levels may be studied to identify the possible serious failure events, before conducting risk evaluation and design review.

The bottom-up safety assessment approach can be used inductively to eliminate some level of uncertainties on all failure events of a system and their respective causes. Therefore, compared with the top-down approach the bottom-up approach has the following advantages (Wang, et al, 1998, & 1996):

- .Omission of system failure events and their respective causes is likely.
- It may be more convenient to be incorporated into a computer package.
- It may be more suitable to be applied to the design of complex offshore engineering systems.

However, both the top-down and bottom-up approaches can be integrated into the design for safety process. The top -down approach is used to focus on areas of special concern while the bottom - up is used to explore the areas in detail. Once the top events of the system have been identified, consequence analysis can be carried out to study the possible effects caused by the occurrence of each identified top event. They may be quantified by experts regarding the particular operating situations.

2.6 *Inherently safe design method*

Adoption and/or application of principle of inherently safe design from the early stages of the design process of offshore installation became necessary following recommendations contained in the Cullen report (Department of Energy, 1990). The design for safety framework has been proposed to incorporate the application of the safety assessment methods using the information generated with increase in details as the design process progress. This increase in information will facilitate the safety assessment to progress from the qualitative to quantitative basis and from assessment function to a decision-making function and eventual movement to a verification function in order to ensure that the final design is in conformity with the desired level of safety.

The proposed inherently safe design methodology for offshore installation made up of the following;

- Problem definition
- Risk identification
- Risk estimation
- Risk evaluation
- Design review

Inherently safe design concept is an iterative process where for example the information generated from the design review may be used to conduct the task of risk identification alongside the design goals defined in the problem definition phase. The various phases for offshore installation will be described in details in relation to the general inherently safe design principles.

2.7 *Inherently safe design Constraints*

In the design of offshore engineering oil & gas platforms, there are still some problems associated with the application of inherently safe design techniques to achieve ultimate solutions to safety based decisions during the design process . Some constraints or difficulties associated with the application of these techniques in the design process are highlighted as follows (Wang and Ruxton, 1998):

- Insufficient data is available in most cases while in some cases it is difficult to obtain such data, this result in having very poor statistical accuracy.

It is extremely difficult to carry out “design for safety” or produce mathematical model for a

- project which is affected by many factors such as design, manufacturing, installation commissioning, operations and maintenance.
- The decision making process is made so difficult due to the combination of the difficult task of defining the scope or extent of "design for safety" at the beginning, and the enormity of work and the associated cost of process of quantifying safety.
- The high level of uncertainty associated with the quantification of effects and consequences of hazard constitute some difficulties to the "design for safety" process.
- The quantification of risks involves significant number of assumptions, estimations, judgements and opinions which are often subjective thereby requiring the involvement of a very skilful safety analyst to interpret the results.
- It is extremely difficult to set up absolute criteria for safety acceptability as safety is only a part of the important requirement for the appraisal of the acceptability of an industrial activity.

3 LESSON LEARNT FROM AN OFFSHORE PLATFORM DISASTER

The worst accident in the history of offshore oil exploration occurred in the North Sea on July 6, 1988, when the Piper Alpha oil drilling and production platform exploded and was consumed by fire. One hundred and sixty-seven workers perished. Oil production in the field was resumed in February 1993 after having been suspended for 5years. The accident was a result of combination of human and design errors which could have been minimised if operators were involved at the early design stage and the conceptual layout eliminated the risk of input from other platforms in such situations.

The level of destruction and loss of lives will have been minimised if the design has integrated a system which will isolate the distressed platform..

Several factors were found to have caused the explosion on Piper Alpha, and many other factors exacerbated the damage and loss of life that followed. Among the deficiencies which could have been eliminated or reduced through the design process are as follows:

a) Lack of an in built system in place to tag or lock out valves consistently, except during major shutdowns.
b) The design team may not have adequate information needed to deal with certain human errors at the early stage of the design process.

Investigation revealed that the work permit system "put too high a premium on informal communications" and that the explosion "can well be understood against the background of informal and unsafe practices" on the Piper Alpha platform. The Piper Alpha accident clearly indicates the need for a comprehensive system based on the principles of inherently safe design to deal with all possible safety issues from human to operations.

The design of BP ETAP platform against gas explosion has addressed some of the design based problems highlighted in the Piper Alpha case.

4 AN EXAMPLE

The design of BP platform in the Eastern Trough Area Project (ETAP) against gas explosion demonstrates a typical example of practical application of principles of inherently safe design using top-down risk assessment methodology. This example deals with the worst case scenario where hazardous situation can escalate to explosion following a fire as was the case in Piper Alpha.

The design approach for the project was to minimise gas explosion risk at an early stage or reducing the risk to ALARP. This project was built on the experiences of BP Andrew project. Accordingly the BP ETAP project was found to be successful in meeting the project objectives (Peterson *et.al*, 2000).

The design in general started with the enlargement of the design team to include safety specialist. The first deign activity is the 'concept selection' where a number of design alternatives or options are studied. Following the selection of the desired option was the commencement of front-end engineering design (FEED). The FEED was used in this project to further develop the design to sufficient level to produce cost estimate within acceptable limits. The detailed design stage was where the specifications were produced for fabrication and construction of the platform.

During the design process, the safety specialist made significant contribution which facilitated the application of advance explosion modeling tools in the selection of the appropriate concept and some early activities of FEED. This process is in contrast with the traditional approach where conventional safety methods are applied at the early stage of the design while safety specialists and advance modeling tools are considered at the later design stages. The principles of design for safety applied in ETAP project against gas explosion are described in the follows sections (Peterson *et.al, 2000*).

4.1 *Conceptual design phase*

At this stage the following design actions were carried out.

4.1.1 *Concept definition*

Definition of the general shape of platforms where various concepts options were evaluated for their explosion risk potentials and possible design modification needed to contain these potentials within the project set target.

In the case of ETAP project the concept selection was based on four deck process modules with separate accommodation module connected by two bridges. The explosion over – pressure loading is the main determinant factor in both the layout and overall structural c onfiguration of the large process modules. In order to comply with this requirement each process deck was divided into three compartments using blast walls. The concept of minimum width for each of the flame travel was used to determine the sizes of each c ompartment while aspects ratio parameter was used to determine the decks height.

The BP Andrew project (Tam, 1996) established that the ratio for a three open -sided volume area should be less than 3 in order to effectively manage gas explosion over -pressure. In attempt to achieve optimum efficiency a maximum ratio 2.5 was used in the case of BP ETAP project

Sizes of compartment were determined at the conceptual design phase of the project to which resulted in the effective establishment of an optimum arrang ement of topside facility. The minimum width concept was used to achieve solid arrangement needed to ensure structural support with adequate strength and ductility properties for blast conditions.

4.1.2 *Project explosion control target*

The BP ETAP project explosion over -pressure target was set at a maximum of 1.5 bar based on the results and experiences gained in the previous projects, and a number of simulations. This target was used by the design team to ensure that all disciplines were focused on design optimization. The designers based their experiences to suggest possible use of technology available to control aver - pressure to less than 1 bar for the theoretical worst case in all areas of the platform.

4.1.3 *Selection of concept options*

Appropriate expertise and tools were used to conduct the process of selection of various options based on judgement of the explosion experts and previous project experience without any calculation involve. However, some level of calculations was conducted in order to ensure that targ et is exceeded.

4.2 *Front-end engineering design (FEED) phase*

At the early stages of FEED, major optimisation of the equipment layout and structural definition were carried out. In contrast with the traditional approach, the design team used computational flui d dynamics (CFD) explosion called Flame ACcelerator Simulator (FLACS) which they successfully integrated into the design process.

The problem of escalation as witnessed in the Piper Alpha case was targeted for control in this project. Some level of control of explosion over - pressure was achieved by ensuring that both the processes of minimisation and design were simultaneously carried out. This approach facilitated the optimisation process through the modeling at every stage from compartment shape, major equipment alignment and location, major pipe -work to minor pipe -work layout and so on. The project team attributed successes achieved at this stage to an enlarged and integrated design team.

4.3 *Detailed design phase*

Much of the efforts at this phase were devote d to minimising the impact of late design installations, such as heating, ventilation and air conditioning (HVAC), ducting, cable trays and electrical panels even though the requirements for them were approximated during FEED. The efforts were to ensure implementation of design specifications made at FEED. The details at this stage were packaged in a computer aided design model (PDMS) which was used for gas explosion modeling work for the ETAP project.

The result achieved by using inherently safe design method can be summarized as follows:

4.3.1 *Control of explosion -over pressure and risks*

The final calculations showed that the maximum gas explosion over pressure on key structural surfaces in all areas were well within the project target of less than 1.5 bar. In most of the areas, they were substantially lower. This process resulted in low individual risks as segregation by compartment reduced the percentage of people to be affected by any major gas explosion. A combination of controlled gas explosion size and large separation distance between potential explosion sites and the temporary refuge (TR) ensure that the TR impairment is zero.

4.3.2 *Verification of as-built design*

For final verification, a site survey was carried out on the modules just before they were floated out. It was found that the geometric models constructed from the project PDMS (Plant Design Management System} computer database gave a good representation of the as-built platform. This provided assurance that calculations carried out during the detailed design were valid. The

5 CONCLUSIONS

In the design process of complex offshore installation, it is necessary to examine the application of principles of inherently safe design to identify and assess potentially hazardous situations and associated risks in order to provide rational basis for determining where risk reduction measures are required. In such a process, either a top-down or a bottom-up safety assessment approach can be used either separately or in combination to study serious failure events and their scenarios. The decision as to which kind of analysis is more appropriate is dependent on the availability of failure data, the degree of interrelationships of the design and the level of innovation in the design.

A safety management framework has been proposed to provide a basis for development of design for safety methodology and modeling for the assessment of safety of offshore oil & gas platforms. An example is used to demonstrate the proposed management framework in the application of inherently safe design techniques on BP platform in the Eastern Trough Area Project (ETAP).

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