Occupational Risk Model for Offshore Oil and Gas Operations

by

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ABSTRACT

The rapid expansion of the offshore oil and gas activities into deeper waters and harsher environments has burden the industry with taking higher risks for developing fields. The lessons learned from past major accidents have shaped the today's health, safety and operational requirements of the industry. Major efforts have been invested in development of analytical approaches to address occupational accidents of catastrophic proportions (high-severity, low-frequency). However, there is a lack of similar tools for accidents characterized as low-severity, high-frequency, which impose similar risks.

To address this gap, the Attwood's reliability model (Attwood 2006) which was originally developed for the quantification of occupational accidents in the oil and gas industry has been revised and enhanced from a deterministic framework to a probabilistic approach. In addition, Attwood's model was extended to be used as an occupational risk estimation tool. The following important modifications were made: development of a probabilistic approach and use of Monte Carlo simulation, development of appropriate model calibration procedures, implementation of mathematical, computational codes and statistical tools, modification of expert survey analysis and finally, risk estimation. The final product is a useful tool for: prediction of occupational accidents likelihood on a specific offshore platform, estimation of accident rate, allocator of resources to specific key entities of the model to produce optimal safety results as well as occupational risk estimator. At the end, recommendations are provided to further advance the state-of-the-art.

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I am a firm believer that apart from our personal efforts, the success of any project depends largely on the encouragement and guidance of many others around us. I take this opportunity to express my gratitude to the people who have been instrumental in the successful completion of this work. I would like to express my sincere gratitude to my classmate and friend, Ghaffar Keshavarz, for his support and guidance in the numerical aspect of this thesis. To my parents, for all their encouraging words, help and unconditional love in every single challenge I have taken in my life. Last but not least, a very special thanks goes to my dear husband, Arash Zakeri for his support throughout my masters program. His love and encouragement, made it possible for me to complete this thesis successfully.

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1 INTRODUCTION

1.1 General

To meet the world's energy demand, oil and gas offshore operations have been constantly moving into deeper waters and harsher environments. Given the particular characteristics of the offshore oil and gas industry and the harsh environmental working conditions, significant accidents have occurred in the past. Those events have shaped today's occupational health and safety requirements and operational guidelines for the industry.

The industry, regulatory organizations and the research community have exerted significant amounts of efforts and resources into studying major accidents which are often considered of low-frequency, but high-severity type of incident. As such, sophisticated analytical models have been developed to address occupational accidents of catastrophic proportions (high severity and low frequency). However, there is a lack of similar tools for accidents characterized as low severity and high frequency, which impose similar danger overall (Attwood 2006, Khanzode, Maiti et al., 2012). Attwood (2006) developed a numerical approach to predict those accidents characterized as low severity and high frequency using a deterministic approach. Occupational accidents involve all accidents or injuries that happen in a work environment. This research however deals only with those occupational accidents categorized as low severity–high frequency in the offshore working environments which represent a large percentage of all reported accidents.

1.2 Overall Objectives of This Research

The overall objective of this research is to enhance the quantitative model for occupational accidents probability prediction presented by Attwood (2006) by changing it from a deterministic approach where the model parameters consist of single average input values to a probabilistic framework whereby probability functions describe model parameters. In a probabilistic approach, techniques such as the Monte Carlo Simulation can be used to obtain a wide range of possible outcomes and their likelihoods. Furthermore, to set bases for a risk estimation tool using accident likelihood model output for:

- prediction of occupational accidents likelihood on a specific offshore platform,
- estimation of accident rate,
- allocation of resources to specific key entities of the model to produce optimal safety results, and
- estimation of occupational risk.

1.3 Overview of the Present Research

The reliability base model for the estimation of occupational accidents in the offshore oil and gas industry, proposed by Attwood (2006), intents to cover the gap of occupational accident research in the oil and gas industry. The idea of this model originated with the recognition of several similarities between the components of the accident process and a reliability network (interconnections of a mechanical/electrical engineering system). One of the novelties of this model is its holistic approach; which considers the influence of societal factors, organizational factors, and factors directly related with the overall system in the occupational accident causation. Another advantage of this model is the introduction of expert opinion, which helps to update constantly the ever-changing environment of offshore installations. The model was specifically designed for offshore operations and it is relatively simple to understand and to apply.

In this research important modifications and further extension of the model have been done to improve the original idea. Changes are briefly listed as follow:

- Development of a Probabilistic approach: The model variables have been introduced as probabilistic values (functions describing variable characteristics) with the objective of representing more realistically the uncertainty associated with each one of them in order to reproduce more reliable probabilistic outcomes.
- Modifications in model calibration: Important modifications and correction to previous approach have been implemented for the model calibration. The model has been calibrated using global data as an equation with seven unknowns. Large amount of data and data analysis from the oil and gas producers (OGP) reports (from 2000 to 2012) were required for this task. Regional OGP data (from seven regions worldwide) were used to solve the proposed new equation using MATLAB.
- Development of Monte Carlo simulations to get probabilistic outcomes of the model: This approach was an entirely new contribution to the model. Monte

Carlo simulations are widely used in risk analysis, given that there is significant uncertainty in variable inputs as it is the case in the Reliability Model.

- Modification in expert survey analysis: Important modifications have been implemented to this portion of the research in order to fit the changes applied to the model.
- Testing and validations.
- Risk estimation: This is an entire new step implemented to the model for the occupational risk assessment of offshore operations.

This revised model can:

- Predict the likelihood of occupational accidents on a specific offshore platform,
- Estimate accident rate within an industry sector,
- Provide the means to effectively direct resources deployment to produce optimal safety results.
- Provide the means to assess the reliability of model predictions (uncertainty analysis).
- Estimate of risk of occupational accidents in the offshore oil and gas industry.

The revised model is an important step forward towards occupational risk assessment evaluation in offshore platforms. The revised model may be used for the calculation of accident frequency (the accident frequency is the probability of an occupational accident happening in an offshore platform in a given year) and design of safety measures to minimize risk.

1.4 Thesis Structure

A brief description of the background information that motivated this research is given in Section 2 followed by a thorough literature review specific to this research in Section 3. The research methodology including the theory behind the base case Attwood (2006) model and its associated model parameters is presented in Section 4. The results of the analyses and simulations including the calibration procedures and risk estimations have been discussed in Section 5, followed conclusions and recommendations for future research to advance the state-of-the-art.

The supporting documents and materials have been appended to this thesis. Appendix I summarize the safety performance indicators processed from the Oil and Gas Producers database of total recordable injury rate (TRIR). The database includes data from 2000 to 2011. The survey responses obtained from expert opinions for Influence Coefficients and Strength Values were normalized before use in this work. The results are included in Appendix II.

Appendix III comprises the MATLAB code written to solve the seven unknown elements of the Reliability Model. Appendix IV presents the MATLAB code to obtain the two-parameter Weibull distributions for each of the seven reliability elements.

2 BACKGROUND INFORMATION

The offshore oil and gas industry has changed dramatically in the last decades, showing an exponential growth when compared to its beginning. The changes are mainly occurring due to the decrease of available shallow water resources, increase in demand and the rapid advancement in technology. Currently, Perdido is the world's deepest offshore oil drilling and production platform, moored in 2,450 metres of water in the Gulf of Mexico. This infrastructure has opened up a new frontier in deep-water oil and gas production (Shell Global 2010).

Given the particular characteristics of the offshore oil and gas industry and the harsh environmental working conditions, significant accidents have occurred in the past. Those events have shaped today's occupational health and safety requirements and operational guidelines for the industry. Examples are: the Grand Banks of Newfoundland (1982), with the loss of 84 lives; the fire and explosions on the Piper Alpha production platform in the North Sea (1988), with a loss of 167 lives; or the most recent "Deepwater Horizon" accident in the USA Gulf of Mexico (2010) that claimed the lives of 11 people and was declare as the worst oil spill in the USA history. As a result, newer and stricter standards and regulations are set in place worldwide. Therefore, there is a major interest from the government agencies, private sector, and scientific communities to continue improving the safety conditions of offshore installations. As an example, on June 10th 2013 the European Union (EU) adopted a directive on safety of offshore oil and gas operations.

This directive covers the entire cycle of exploration and production activities and has the objective of ensure that the highest safety standards will be followed at every oil and gas platform across Europe (EU 2013).

Considering that occupational safety can be defined as the control of recognized occupational hazards in order to achieve an acceptable level of risk. Then, the estimation of risk levels and the assessment of their significance has currently become an important tool for comparison with acceptance criteria and reduction of risk levels in the work environment.

As stated by Khanzode, Maiti et al. (2012) in their comprehensive review of accident research, major efforts have been invested in occupational accidents of catastrophic proportions such as explosions, burns, and air or water transport accidents. These accidents are characterized for its high severity–low frequency and have a high impact in the public opinion. However, Khanzode, Maiti et al. (2012) noted in their review that risk assessment techniques do not quantify risk of occupational injury to an individual, per se.

Attwood (2006) also stated, “occupational accidents that in comparison can be considered of minor severity such as slips, trips and falls can impose similar danger overall, than the low frequency-high severity ones”. He based his conclusion from the International Association of Oil and Gas Producers (OGP) data for the years 1998 to 2002 and documents from the UK HSE, 1996 both of which indicated that over a third of all reported major injuries result from slips or trips, are considered the single most common cause of injuries. Attwood (2006) recognized that there was a lack of quantitative models for the estimation of this particular type of occupational accidents in the oil and gas industry and developed a Reliability Model for the Quantification of Occupational Accidents to cover this gap.

Figure Figure 2-1 and Figure 2-2 show the summary of OGP data corresponding to two safety indicators. Fatality and lost work day cases for the years of 2009 to 2011. **Error! Reference source not found.** illustrates fatalities reported by OGP on offshore and onshore activities. The fatality safety indicator shows that "occupational accidents" (struck by, falls from height and caught in or under) represent approximately 45% of the data.

Figure 2-2 represents data exclusively for offshore activities and shows that "occupational accidents" represent approximately 75% of the data.

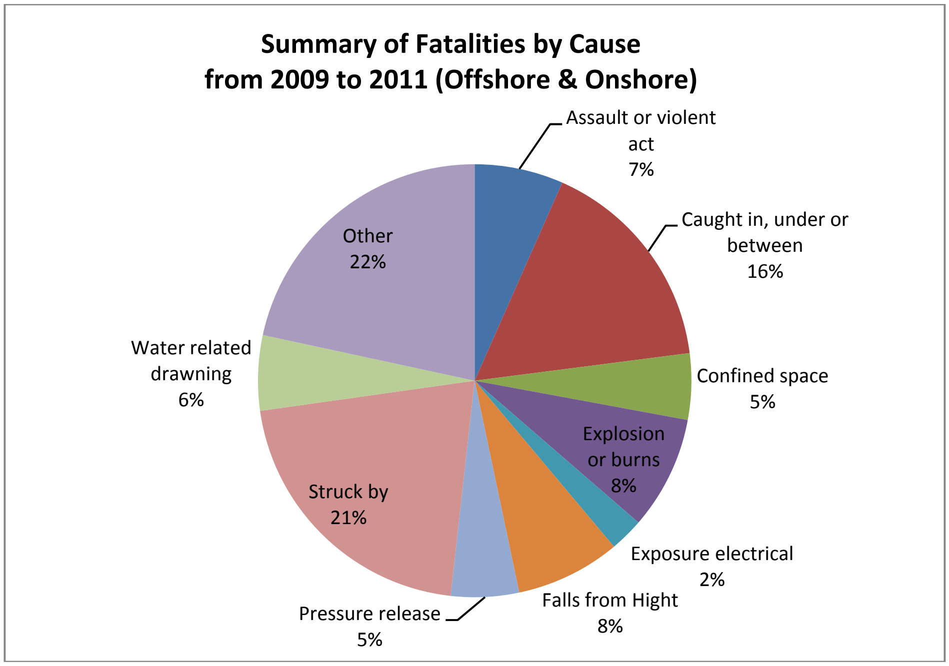


Figure 2-1 **Summary of Fatalities by Cause for the Years 2009 to 2012 (International Association of the Oil and Gas Producers, 2009, 2010 & 2011)**

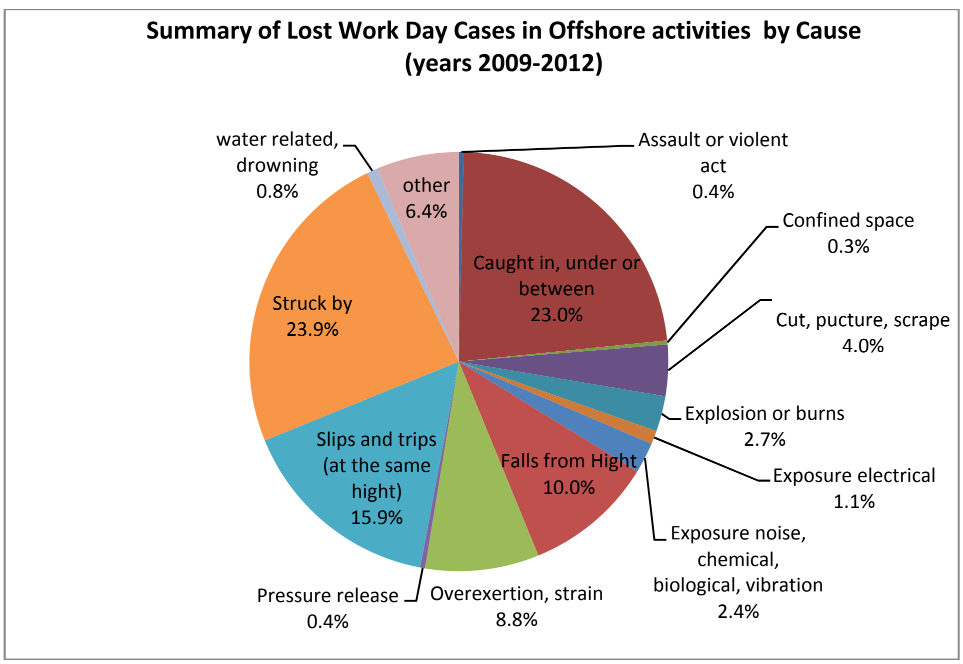


Figure 2-2 **Summary of Fatalities by Cause for the Years 2009 to 2012 (International Association of the Oil and Gas Producers, 2009, 2010 & 2011)**

Both figures above confirm Attwood's (2006) conclusion that it is evident that accidents categorized as more frequent and less severe (e.g. struck by, falls from height, caught in between and under, etc.) represent a considerable percentage of the overall reported occupational accidents.

Occupational accidents involve all accidents or injuries that happen in a work place that results in injuries to workers. However, the term occupational accidents in this research is used (unless otherwise specified) to estimate the accidents categorized as low severity–high frequency in the offshore working environments; which as stated above, represent a large percentage of all reported accidents (such as struck by, slips and trips, falls, caught in under or between, etc.).

Over the recent years, numerous models and theories have been developed aiming to improve the organization's safety performance. However, there is still more work to do for the specific conditions of offshore operations. It is been recognized that to reduce the likelihood of occurrence of accidents, it is essential that scenarios involving the potential loss of operational control need to be assessed at early stages. However, it is important to recognize that offshore activities are often associated with high levels of uncertainty for the following reasons: they usually operate in a constantly changing environment; offshore installation are complex and expensive engineering structures composed of many systems and each one of them are usually unique with its own design and operational characteristics (Wang, Sii et al. 2004). On the other hand, it is important to acknowledge that human and organizational elements significantly influence the safety of offshore installations (Ren, et. al., 2009). Therefore, the need of integrated models with flexible approaches to facilitate its application continues to exist.

3 LITERATURE REVIEW

3.1 Overview of the Offshore Oil and Gas Industry

The offshore oil and gas industry started about six decades ago, when in October 1947 a mobile rig drilled in approximately 4.3 meters (14 feet) of water in the open Gulf of Mexico's Ship Shoal Area. The world offshore oil and gas industry has changed dramatically since then. Nowadays, the technical capabilities, the number of people working in this industry, and the rate of oil production in this particular sector all show an exponential growth when compared to its beginning.

Historically, the highest levels of activities are conducted in regions of the North Sea, Gulf of Mexico, the South China Sea, and the Caspian Sea. However, more recently, offshore operations have expanded to West Africa, India, and the deep waters off the coast of Brazil and Eastern Canada. It is estimated that approximately 60% of the world's petroleum production comes from offshore operations in waters of more than half the coastal nations on earth, including Canada (Ministry of Energy 2012).

The challenging working conditions of offshore oil and gas platforms are well-known. Significant accidents have occurred in the past in this particular industry. These accidents have attracted public concerns at all levels. Accidents such as the one of 1982 on the Grand Banks off Newfoundland, with the loss of 84 lives; the 1988 fire and explosions on the Piper Alpha production platform in the North Sea, with a loss of 167 lives; or the recent 2010 BP oil spill disaster that claimed the lives of 11 people and was declared as the worst oil spill in the USA history. All of them have result in stricter regulations for the offshore oil and gas industry with respect to the environment and occupational health and safety issues.

Subsequently, the need to improve safety planning and performance for the offshore oil and gas industry has become a very important subject in the last decade. The offshore Oil and Gas (O&G) sector, researchers, government agencies, and various organizations are directing resources to improve their ability to respond to those new growing demands in safe and sustainable manner.

3.2 Particular Features of Working in Offshore Environments

Several features of offshore work have direct impact on the way occupational health and safety has been practiced in this sector and the way that they are addressed (Gardner 2003). The main features described by Gardner (2003) are:

- Physical isolation; the installation are mostly isolated and the workers have to travel typically by helicopter and stay in the platform for long periods of time.

  Major hazard potential; the Piper Alpha disaster in 1988 tragically illustrates why safety is a primary concern of offshore managers. Offshore platforms are usually designed in an extremely compact layout, which has a high density of equipment.

In high pressurized systems the potential of accident occurrence and its consequences are considerably high.

- Shift and tour patterns; offshore workers work 12 hours shifts each day to a variety of patterns, over a two or three week “tour”, with varying periods of leave between tours.
- Aging workforce; many workers have worked offshore for over 20 years and on some installations the average age of the workforce is in the late forties. The effect of aging on an individual’s ability to work in offshore conditions and his/her changing vulnerability to health stresses and accidents in the working environment has hardly been examined.
- Multiple exposures; work offshore can involve exposure to a range of hazards sequentially or simultaneously (e.g. hazardous substances, noise, vibration, hot or cold conditions, heavy manual handling activity are all present on the drill floor). Additionally, potential interactions between different stressors such as the ones mentioned above have hardly been explored.
- Environmental concerns; worker exposure to hazardous substances offshore can be affected in various ways by environmental concerns. Thus, the substitution of less environmentally hazardous materials can introduce others that are potentially more hazardous to the worker. For example, the removal of various ozone-depleting chemicals under the Montreal Protocol led in some cases to changes to more toxic or asphyxiating, fire-fighting gases (such as carbon dioxide and nitrogen).

3.3 Occupational Accidents in the Offshore Oil and Gas Industry

An offshore installation is a complex and expensive engineering structure composed of many systems and it is usually unique with its own design and operational characteristics (Wang, Sii et al. 2004). Offshore installations need to constantly adopt new approaches, new technologies, new hazardous cargos among others and each of these changes brings a new hazard in one form or another. One of the major challenges in the practical application of formal offshore installation safety assessment is associated with the development of integrated and flexible approaches to facilitate its application, while human and organizational elements significantly influence the safety of the offshore installation (Ren, Jenkinson et al. 2009).

In general, occupational accidents in the offshore oil and gas industry can be classified in the same way as for any other industry. The following sections describe briefly the main definitions and the classification of accident models and the theories to set the bases for this research project.

3.3.1 Accidents and Injuries Definition and Classification

In general accidents can be defined as a hazard materializing in a sudden probabilistic event, or chains of events with adverse consequences (injuries). Occupational accidents are distinguished from other accidents by the facts that they happen in a working life context and that the main consequences are limited to injuries on the involved workers.

Furthermore, the worker is often the agent as well as the victim of the injury (Hovden, Albrechtsen et al. 2010).

Injury and accident are closely related terms and often, the terms are used synonymously (Khanzode, Maiti et al. 2012), though they are not synonyms. Every accident does not necessarily result in human injury, but every injury is a result of an incident that can be termed as accident. Causal factors are responsible for transforming injury risk into an incident. The injury level determines how this energy is transferred to the victim's body and what is the severity associated with it. Based on all this sequence the occupational accidents can be divided into five categories (Khanzode, Maiti et al. 2012). These are:

- hazard identification methods,
- injury risk assessment methods,
- accident and injury causation theories
- injury mechanism, and
- accident and injury intervention methods.

A summary of each one of this classification is presented in Table 3-1. This classification also presents information regarding other important accident models such as SHIPP (Rathnayaka, Khan et al. submitted) and STAMP methods (Leveson 2004).

Table 3-1 Summary of Occupational and Accident Classification

Broad area of research	Criterion for Classification	Category	Brief Description
Hazard identification Includes identification of hazardous energy sources and identification of hazardous processes and situations in a work system.	Search technique	Backward tracking Forward tracking Morphological	Approaches can be further divided in three categories: Biased reactive approach, analysed after occurrence of an accident; Biased proactive approach, depends heavily in previous knowledge of the system, backward and forward tracking methods fall under this category (i.e. Fault tree analysis(FTA), Event tree analysis (ETA), cause consequence analysis, Failure Mode Effect Analysis (FMEA), Failure Mode Effect and Criticality Analysis(FMECA); Unbiased proactive approach, hazard analysis is carried out without waiting for the events to occur and restrictive hazards assumptions, morphological methods fall in this category (i.e. hazard and operability (HAZOP), management oversight, risk tree (MORT) and system hazard identification, prediction and prevention (SHIPP) methodology.
Risk Assessment Risk assessment involves identifying potential threats, estimating their likelihood, and estimating the consequences	Criterion variable Indices are employed to estimate risk of accident/injury (descriptive statistic). Indices may be Lost-time injury frequency rate (LTIF), fatal accident rate (FAR), etc Modeling technique Various models are proposed for assessing accident/injury risk.	Injury rate Lost time injury rate Severity index Occurrence probability Statistical distributions Soft computing Categorical scales	Risk assessment methodologies are classified as: Qualitative methods and quantitative methods. These categories can further be classified as deterministic, probabilistic, and combinatorial approaches. Quantitative methods are suitable when the risks are high, costs of detailed analyses are justified, and relevant data is available. The results are represented in the form of risk profiles. Qualitative risk assessment is more suitable when risks are low and small number of categories can cover entire range of consequences and likelihoods. The results are represented in the form of risk matrices. Risk assessment process Includes two decisions: i)selection of criterion variables, and ii) Selection of modeling techniques.
Accident Causation There are a number of accident examined by researchers over the years, these theories and models can be divided into four generations	Generation	Gen-I: Accident proneness theory Gen-II: Domino theory Gen-III: Injury epidemiology	First generation (Gen-I) theories hold a primitive viewpoint towards accident causation. These theories hold a person's traits and unsafe behavior as responsible for accident. Gen-II theories conceptualize a chain of sequential events leading to an accident, and call these events as dominos. Gen-III, injury epidemiology approach holds that accident prevention efforts do not necessarily lead to injury control in a work system. Uncontrolled energy transfer focused, control at pre-injury, injury and post injury stages.

Broad area of research	Criterion for Classification	Category	Brief Description
		Gen-IV: System theory STS theory	Gen IV, Holistic approach, Integrated safety systems. Interacting social and technical subsystems (STS), Job design based on STS principles. According to STS approach, a system is composed of two interacting subsystems: social and technical subsystem. Joint optimization of these subsystems leads to better performance of the whole system.
Injury Mechanism Injury models attempt to explain how the energy that is transferred to a human body is built in a work system, and what causes release of uncontrolled energy.	Energy interaction	Deviation Models Energy Models Severity Models	Deviation models explain injury on the basis of deviations occurring in the system variables which lead to release of uncontrolled energy. Energy models describe the phases in injury mechanism in slightly different terms as compared to deviation models. These phases are: energy build-up phase, energy release phase and impact phase. Examination of factors affecting injury severity in different work systems is helpful in minimizing the severity of impact, and reducing lost man-days under a given situation. Factors affecting injury severity are not exactly the same as the factors causing injury. Major and fatal injuries are caused by different factors as compared to minor and nonfatal injuries.
Injury Intervention Strategies based on the following principles: (i) isolating the source of energy release, (ii) separating the source and the user in time–space, (iii) providing protecting envelope around the user, (iv) providing instruction and information, so users can operate rationally in presence of energy release.	Intervention type	Engineering Behavioral Enforcement	Engineering interventions generally adopt an approach called ‘‘design for safety’’ or ‘‘integrating safety into design’’, i.e. personal protective equipment (PPE). Behavioral intervention is related to education and training interventions mainly focus on behavioral modification. Training generally enhances skill and knowledge on the job, and is effective in reducing injury if lack of skill or knowledge is a strong causal factor for injury. However lack of skill or knowledge is not always a causal factor of injury. With regard to assessment of enforcement interventions towards injury prevention, status of the literature is even poorer. A few researchers examined effects of rules and regulations on occupational safety. Systems Theoretic Accident Model and Processes (STAMP) is an example of it. The most basic concept in STAMP is a constraint, rather than an event. Traditional accident models explain accident causation in terms of a series of events, while STAMP views accidents as the result of a lack of constraints (control laws) imposed on the system design and during operational deployment.

3.4 Risk Relevant Definitions and Concepts

3.4.1 Definition of Risk:

A hazard is considered the source of danger, but the concept itself does not contain any notion of the likelihood. It is often uncertain whether or not a hazard will actually lead to negative consequences. The hazard probability can be quantified. Then, the definition of risk combines both elements “hazard” and “probability” (Bedford and Cooke 2001).

Mathematically, risk can be expressed as a function of hazard and exposure from risk agents causing adverse probabilistic consequences to a receptor, which can be human beings, ecosystem, environment or property.

R= f(hazard, likelihood of exposure, and impact of hazard)

$$R = p \times S \times I$$

Where:

R = Risk

p = Probability of occurrence of an unwanted event

S = Consequence or severity of occurrence of an unwanted event

I = Impact of hazard

As shown above, the level of risk is dependent on the degree of hazard as well as on the amount of safeguards or preventive measures against adverse effects. Since risk is expressed as the probability of occurrence; therefore, uncertainty evaluation plays an important role in quantifying risk.

Kaplan and Garrick (1981) further refined the notion of risk in the following way: Instead of talking about the probability of an event, they talk about the "frequency" with which such an event might take place. They then introduce the notion of uncertainty about the frequency which gives a more sophisticated notion of risk.

3.4.2 Definition of Risk Assessment

Risk assessment is the overall process of identifying the sources of potential harm (hazard) and assessing; the seriousness (consequences or loss criticality), the exposure to any hazard, the likelihood of any adverse outcome that may arise, and the safety level. It is based on hazard, consequence, exposure, likelihood, and safety level assessments leading to an estimation of risk.

Kaplan and Garrick (1981) suggested that risk is most usefully considered as a narrative that answers three questions:

- What can happen?
- How likely is it to happen?

- If it does happen, what are the consequences?

Therefore, an estimate of the level of risk whether qualitative (negligible, low, moderate, substantial, high or very high) or quantitative, is derived from the likelihood, exposure, consequences the scenarios that arise from identified hazards. In addition, uncertainty about likelihood, exposure, and consequences of each scenario will affect the individual estimates of risk. Figure 3-1 illustrates the iterative process of risk assessment and risk reduction.

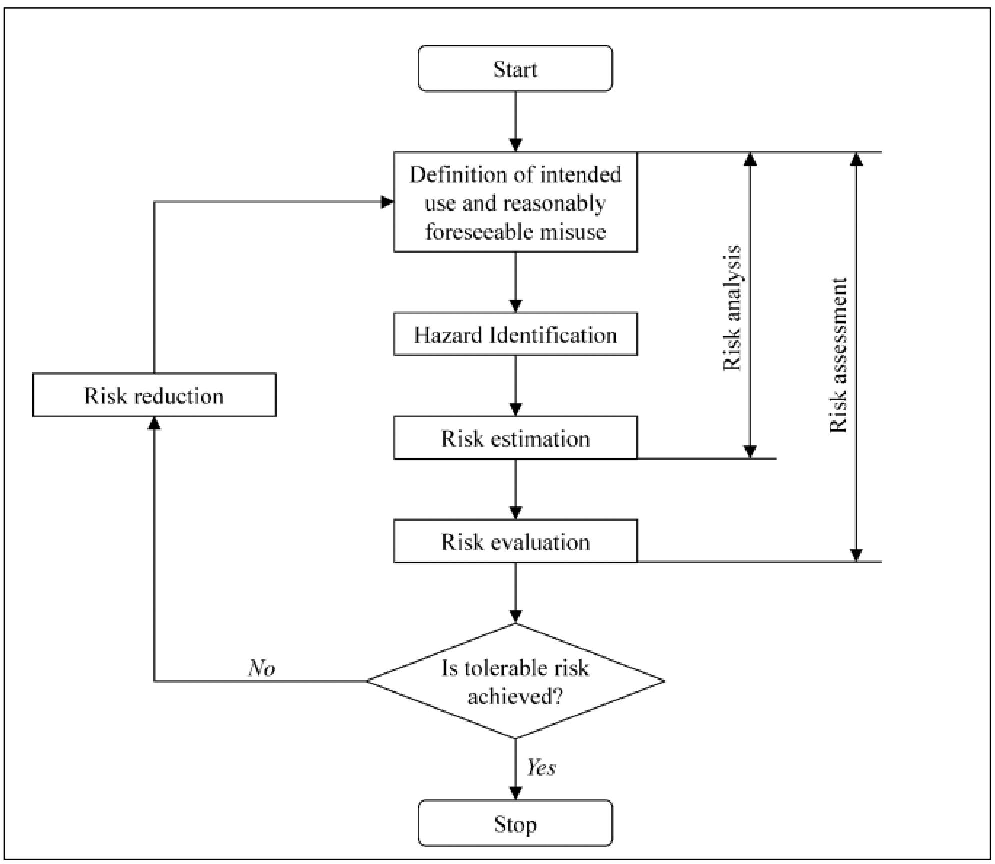


Figure 3-1 Iterative Process of Risk Assessment and Reduction (ISO/IEC, 1999)

The purpose of risk assessment under the international regulations is to identify risks to human health and other environmental targets and estimate the level of risk based on scientific evidence. Risk analysis can be applied to many different types of risk. Different methodologies have been proposed to assess different risks (WHO 2009). Assessment of risks to health and safety often takes the form of hazard identification, dose-response assessment and exposure assessment leading to risk characterization.

Risk assessment methodologies are mostly classified as: i) qualitative methods, and ii) quantitative methods or the combination of both iii) semi-quantitative methods. These categories can further be classified as deterministic, probabilistic, and combinatorial approaches (Radu 2009; Khanzode, Maiti et al. 2012).

3.4.2.1 Qualitative Risk Assessment

Qualitative risk assessment is more suitable when risks are low and small number of categories can cover entire range of consequences and likelihoods (Khanzode, Maiti et al. 2012). Nonetheless, occupational qualitative risk assessment should be a systematic examination of what in the workplace could cause harm to people, so that decisions can be made as to whether existing precautions or control measures are adequate or whether more needs to be done to prevent harm (Radu 2009). Health and Safety England has published guidance on carrying out simple, qualitative assessments in the booklet 'Five steps to risk assessment' (HSE UK 2011). Based on their recommendations, the steps to follow a qualitative assessment are:

- Identify the hazards.
- Identify the possible consequences (decide who might be harmed and how).
- Evaluate risk (and decide whether the existing precautions are adequate or whether more should be done).
- Record the findings.
- Review your assessment and revise if necessary.

The results of a qualitative risk assessment are usually represented in the form of risk matrices where occurrence probability and consequence severity represent the two axes (Khanzode, Maiti et al. 2012).

Table 3-2 Advantages and Disadvantages of Qualitative Risk Assessment

Advantages of Qualitative Risk Assessment	Disadvantages of qualitative Risk Assessment
• Allow the determination of areas of greater risk in a short time and without bigger expenditure • the analysis is relatively easy and cheap	• The results cannot be expressed in numerical measures, therefore does not allow for determination of probabilities • Cost benefit analysis is more difficult due to the lack of numerical values • The results have a general character, approximate.

3.4.2.2 Semi-quantitative Risk Assessment

Semi-quantitative risk assessment provides an intermediary level between the textual evaluation of qualitative risk assessment and the numerical evaluation of quantitative risk assessment, by evaluating risks with a score. Semi-quantitative risk assessment is more suitable in intermediate cases where the hazards are neither few nor simple, nor numerous and complex. In those conditions, it may be appropriate to supplement the simple qualitative approach with a semi-quantitative assessment (Radu 2009).

In carrying out semi-quantitative risk assessments, simple qualitative techniques may be enhance by the use of simple modeling techniques. These simple modeling techniques can help to estimate the severity of the consequences and the likelihood of hazards. Finally, these estimates can be combined to obtain estimates of the associated risk. A number of different techniques for carrying out semi-quantitative risk assessments exist, including risk matrix approaches and lines of defence/layers of protection analysis.

Table 3-3 Advantages and Disadvantages of Semi-quantitative Risk Assessment

Advantages of Semi-quantitative Risk Assessment	Disadvantages of Semi-quantitative Risk Assessment
• It offers a more consistent and rigorous approach to assess risks and risk management strategies than the qualitative risk assessment techniques • avoids some of the greater ambiguities that a qualitative risk assessment may produce • It does not require the same mathematical skills as quantitative risk assessment, nor does it require the same amount of data, which means it can be applied to risks and strategies where precise data are missing	• The risks are placed into usually quite broad sets of categories. It is therefore imperative that the categories are carefully constructed. • Using the semi-quantitative risk assessment scoring system as a surrogate for probability calculations is likely to cause severe inaccuracies when one assesses a longer sequence of events.

3.4.2.3 Quantitative Risk Assessment

Quantitative risk assessment requires the estimation of frequency and consequence severity in quantitative terms. This approach is suitable when the risks are high, costs of detailed analyses are justified, and relevant data are available. The results are represented in the form of risk profiles (Khanzode, Maiti et al. 2012).

Table 3-4 Advantages and Disadvantages of Quantitative Risk Assessment

Advantages of Quantitative Risk Assessment	Disadvantages of Quantitative Risk Assessment
• Allows assessing consequences of incidents occurrence in quantitative way; so, facilitates realization of costs and benefit analysis during selection of protections measures. • They give more accurate image of risk	• Analysis conducted with application of those methods is generally more expensive, demanding greater experience, high technical skills and advanced tools. • Quantitative measures depend on the scope and accuracy of defined measurement scale • It is case specific

Quantitative risk assessment can be further divided into two approaches: deterministic and probabilistic. Both approaches have an important role in the quantitative risk analysis performed for decision making purposes; both methods have advantages and disadvantages. However, one method will have priority over the other; depending on how quantitative are decisions to be made, available data, and the scope of the project.

3.5 Highlights of Relevant Occupational Risk Assessment Models

In this section of the report four different quantitative approaches to address occupational accidents in the offshore O&G industry are summarized and compared. A summary table with the results is presented after the description of each one of the models.

3.5.1 Modeling Offshore Safety Focusing on Human Organization Factors (Ren, Jenkinson et al. 2009)

Ren, Jenkinson et al. (2008) proposed a methodology to model causal relationships among multiple risk factors for offshore operations. The paper states the importance of addressing HOFs in accident modeling based on various studies where it has been shown that HOFs contribute to: 75% of fires and explosions, 89-86% of collisions, 79% of towing vessel groundings and 84-88% of tanker accidents. The approach used in the paper is described in the following sections.

3.5.1.1 Model Overview

The model proposes a combination of approaches between the Reason's "Swiss cheese" model (Ren, Jenkinson et al. 2008), to form a generic offshore safety assessment framework; and Bayesian Network (BN) that is fitted into the framework to construct a causal relationship model. The proposed framework uses a five-level-structure model to address latent failures within the causal sequence of events (Figure 3-2). The five levels include Root causes level, Trigger events level, Incidents level, Accidents level, and Consequences level as shown in the figure below.

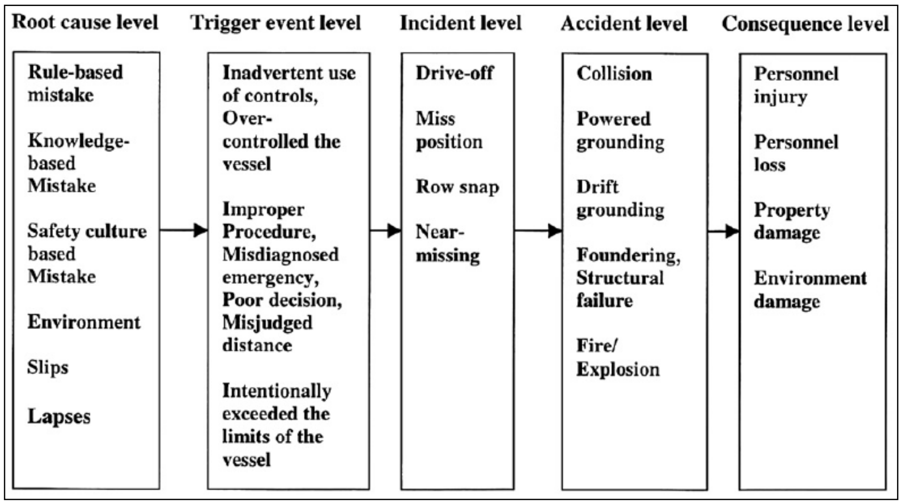


Figure 3-2 The Conceptual Model for HOFs (Ren, Jenkinson et al. 2008)

To analyze and model the safety of a specific offshore installation, a BN model is used following the guideline of the proposed five-level framework. A range of events was specified, and the related prior and conditional probabilities regarding the BN model, were assigned based on the inherent characteristics of each event. As a result, numerical values of occurrence likelihood for each failure event are calculated. To show the applicability of the model a case study of the collision risk between a Floating Production Storage and Offloading (FPSO) unit and authorized vessels caused by HOFs during operations is used to illustrate an industrial application of this particular methodology.

3.5.1.2 Justification of the approach

The paper states that offshore accidents occur through the concatenation of multiple latent errors. An individual error may not be sufficient to cause severe consequences unless it occurs in combination with other latent errors.

Based on human behavior and organizational theory, literature proposes the “Swiss Cheese” model to study HOFs (see Figure 3-3). Each slide of the Swiss Cheese model represent a safety barrier or precaution relevant to a particular hazard. The holes in the cheese slices represent a latent errors (human error, equipment failure, etc.) waiting to happen. The defensive barriers are like dynamic slices of Swiss Cheese against accidents and incidents, with the holes constantly subject to changes in size and location. When the holes line up, meaning that all the defenses fail and a system’s latent vulnerabilities are exposed, then an incident occurs. A significant attribute of Reson’s model is that each of the contributing factors is seen as necessary but no sufficient on its own to cause the occurrence of an accident. However, the Swiss Cheese model is mainly criticized for being simply a conceptual model with few details on how to apply in a real-world setting. This particular weakness can be overcome by BNs that are capable of providing graphical demonstration of inter-relationships as well as numerical values of occurrence likelihood for each failure event.

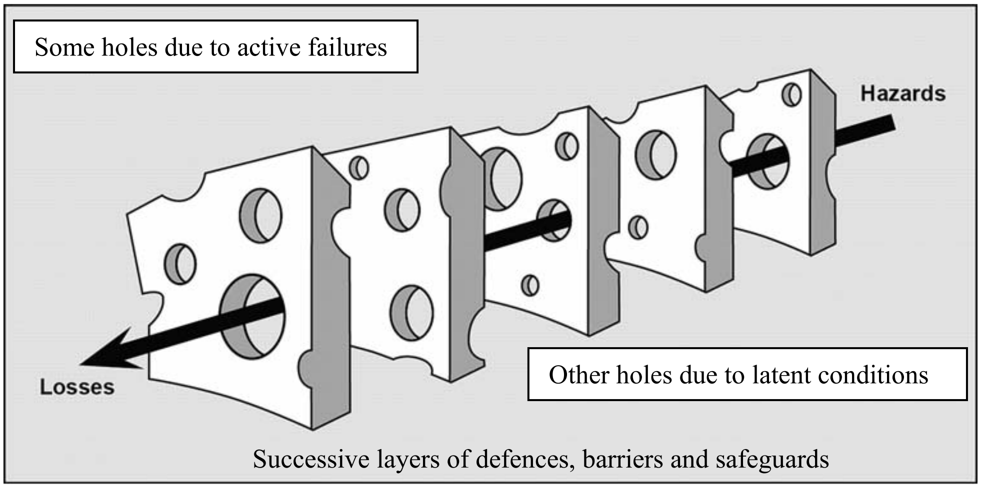


Figure 3-3 Swiss Cheese Model (Ren, Jenkinson et al. 2008)

BN has been increasingly recognized as a powerful tool to support causal inference in situations where data for analysis is with high level of uncertainty, and certainly HOFs involve a high level of uncertainty. The paper describes how BN is capable of replicating the essential features of plausible reasoning in a consistent, efficient and mathematically sound way. BN is mainly criticized for lack of guidelines in establishing a causal model, that is, modeling is heavily dependent on expert's personal experiences and is therefore highly domain specific. The "Swiss cheese" model is such a theoretical framework based on solid behavioral theory and therefore can be used to provide a roadmap for BN modeling.

3.5.1.3 Conclusions

Offshore installation usually operates in dynamic environments in which technical human and organizational malfunctions may cause accidents. As such, HOFs should be considered in any safety assessment. The case study shows that Reason's "Swiss cheese" model and BN can be jointly used in offshore safety assessment.

The paper states that BN uses probability measure to assess uncertainty and thus requires precise information in the form of prior and conditional probability tables. Such information is often difficult or impossible to obtain; in particular, when dealing with indirect relationships. In those cases, verbal expressions such as very unlikely for example could be more appropriate than numerical values. Therefore, the paper proposes that the future work should be to investigate the possibility of merging BN and fuzzy logic to conduct Bayesian reasoning to facilitate offshore risk analysis. The merging of BN and fuzzy logic has already been done (Musharraf, Hassan et al. 2013), this particular research has been detailed further in this document.

3.5.2 Quantifying Occupational Risk – ORM Model (Ale, Baksteen et al. 2008)

Ale, Baksteen et al. (2008) constrcuted of a model called Occupational Risk Model (ORM). The ORM is a result of a project requested by the Ministry of Social Affairs and employment of Netherlands (SZW). It was expected that with this model, industries and experts can evaluate the occupational risk for the individual workers, companies and projects.

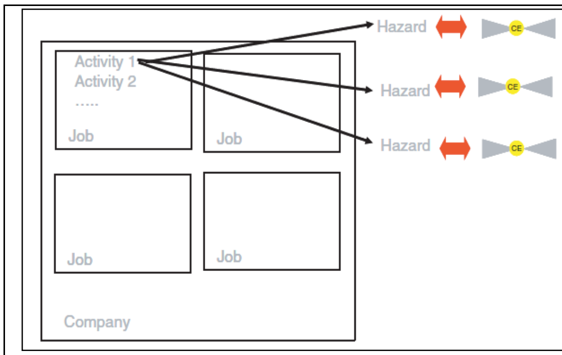
3.5.2.1 Model Overview

The ORM model is a further development of previous work executed with support of SZW and the European Union, such as IRISK and AVRIM. The model has as an objective to support the specifications of the SZW policy. The policy requires quantitative analysis of risk, determination of dominant paths to accidents from these quantifications, analysis of underlying scenarios, and reduction of risk by addressing the dominant threats first and by using the most cost effective method of risk reduction.

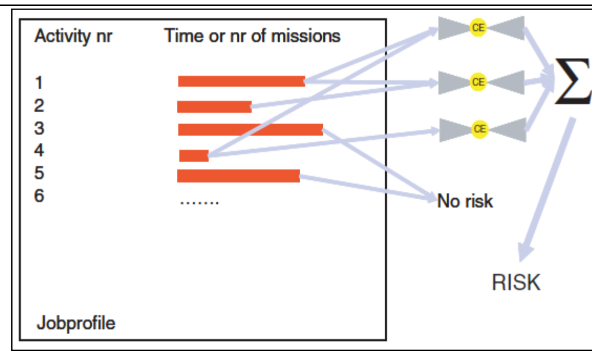
3.5.2.2 Justification of the Approach

The quantification of occupational risk is approached in a similar fashion as the approach taken when calculating the risk of a chemical plant. The risk profile of a chemical plant is constructed from the risks of its components: vessels, pipes, reactors etc. The risk associated to a task is constructed from the risks associated with the hazards a worker has to face when he or she performs his work. Therefore, the work profiles were decomposed according to the data of accident statistics in Netherlands. From these records a list of hazards or causes of accidents are derived. This list is partly based on a classification of accident types used by the Labor Inspectorate in their reporting on occupational accidents, the classifications form the UK and the classification from previous Dutch studies.

The list plays a very important role, since it is required for linking activities and hazards to construct the risk profile of a task or a particular work title. Through activities and hazard list the risk profile for this work-title is constructed by adding the exposures to each of the associated hazards for a full year of employment. The risk of an entire company can then be constructed by combining the risk of the work titles in the company rated according to the number of job positions with that title (Figure 3-4). The resulting risk can be expressed in a wide range of possible metrics. However, the data used will define risk in its own units (i.e. death, permanent injury and reversible injury).



Company, jobs, hazards and Bow-ties



Job profile, exposure, Bow-tie and risk

Figure 3-4 Schematic Representation of the Methodology of the Model Presented by Ale, Baksteen et al. (2008)

Using the list of hazard types as a starting point, the scenarios are systematically analyzed into the chain linking cause with consequences. For this purpose the Storybuilder model was developed. Storybuilder is part of the ORM software that organizes the inspector's reports around single centre events, which are the materialization of the hazards form the hazard list. Thus, Storybuild is constructed for falling from ladders, being hit by falling objects or other scenarios. The Storybuilds developed for this project can be found online (www.storybuilder.eu). The Storybuilds give information about the make-up of the accident and about the distribution of causes and causal chains given that an accident of a certain type occurs. The way that the model works is closely related to the way the risk is logically modeled. The relationship between an accident and its possible causes is often given as a fault tree. The relationship between an accident and its potential consequences is often depicted as an event tree. Coupling both trees at the accident link a Bow-tie shaped diagram results (small bow-ties relations are shown on Figure 3-4). In order to be able to link the Bow-ties with the Storybuilds, the structure of the scenario analyses is shaped in the form of a barrier analysis.

The risk reduction then can be carried out by taking measures. Measures influence the risk and this is reflected in a change in the probabilities of blocks in the logical diagram to be in one of their states. The smallest possible unit of change in the total risk picture of a company is called a probability influencing entity or (PIE). Measures can result from rules and regulations to improve compliance, measures can also be technical. Measures and PIES in ORM are defined by two parameters: the effect on probability and the associated cost.

Finally the optimizer combines the information on the Dutch national average, the information supplied by the user on his specific situation and the information on PIEs -

probability effect and cost –to seek out the optimal combination for risk reduction. From the results the user can choose a combination of cost and risk according to his needs. Figure 3-5 depicts the relations of the three constituents of the ORM (Story builder, Bow-tie builder, and optimizer)

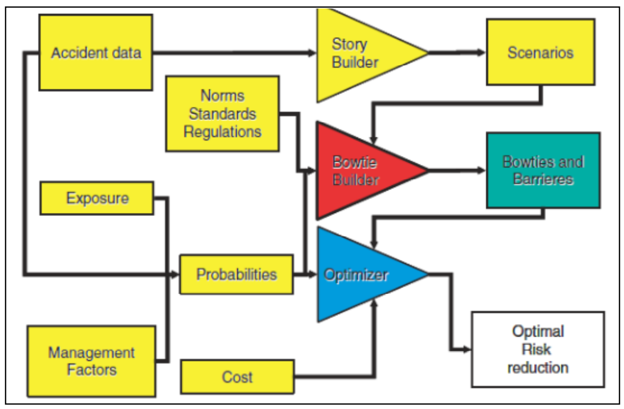


Figure 3-5 The basic ORM Components (Ale, Baksteen et al. 2008)

3.5.2.3 Conclusions

The ORM model is a further development of quantification techniques. The model is developed for use by enterprises and governments in developing strategies to further reduce occupational risk.

3.5.3 Reliability Base Model for Occupational Accidents (Attwood 2006)

Attwood (2006) developed a reliability based model for occupational accident in the offshore oil and gas industry. The model is a holistic quantitative approach. The objectives of the model are: predict the likelihood of occupational accidents on a specific offshore platform, estimate accident rate within this industry sector and, provide a means to effectively direct resources to key entities of the model to produce optimal safety results.

3.5.3.1 Model Overview:

During his investigation Attwood (2006) found the existence of corporate and regional differences in safety performance. Therefore, the model considers three groups of factors or layers, as the ones affecting accident frequency (External layer, Corporate layer and Direct layer). The approach of the model is based on a chain of influence between the layers; originating with external factors, which act through corporate elements, to affect factors directly influencing the accident process (refer to Figure 3-6). Each one of the factors is described below:

- Direct Factors: include individual staff behaviors and capabilities, weather, safety design, and personal protective equipment
- Corporate Factors: provided by the supporting organization, including the level and quality of safety procedures, training, and culture.
- External Factors: such as societal value placed on life and financial pressure such as shareholder pressure, price of oil, and royalty regime.

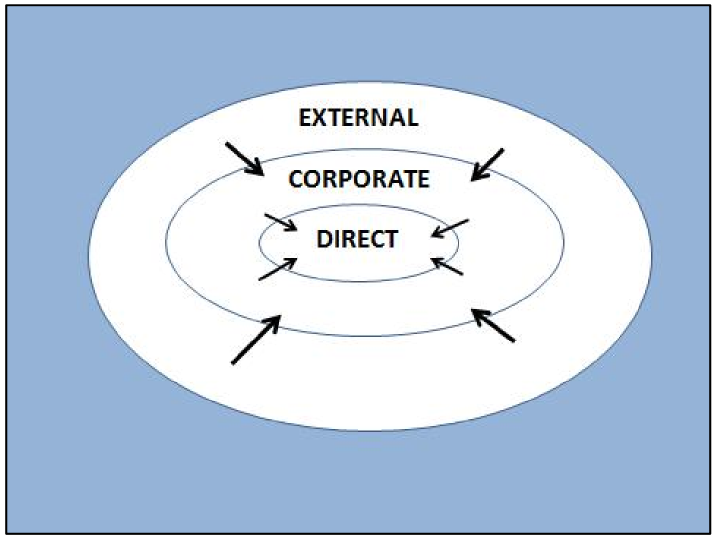


Figure 3-6 Basic Schematic of the Reliability Based Model (Attwood 2006)

3.5.3.2 Justification of the Approach

The accident process was modeled using a modified reliability network. Daryl Attwood's investigations lead to the recognition that there are several similarities between the components and interconnections of a mechanical/electrical engineering system (Attwood, Khan et al. 2006).

As such, the overall system is subdivided into sub-systems, where the arrangement of elements are either in series (i.e. weather, safety design and PPE) or parallel (i.e. the elements that comprise physical capability; coordination, fitness and lack of fatigue). The complete internal arrangement of the elements in the model is shown on Figure 3-7.

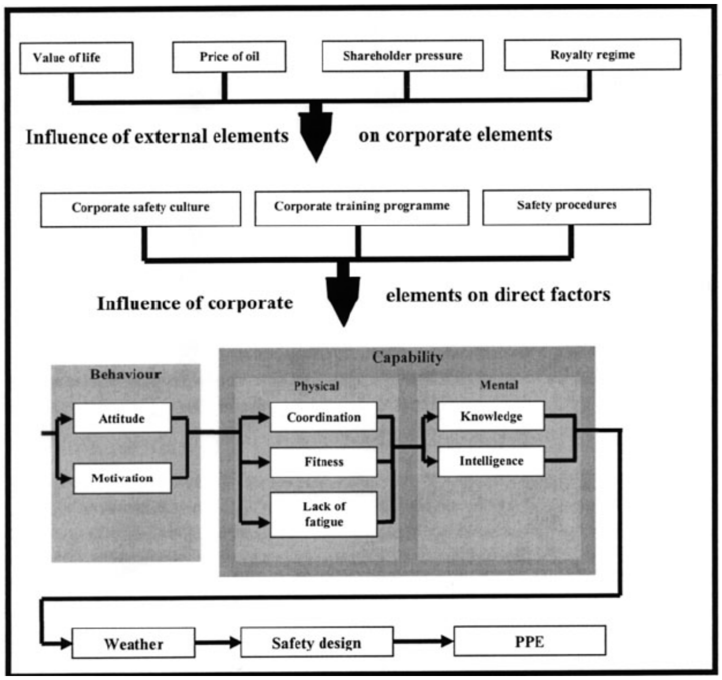


Figure 3-7 Internal Arrangement of the Elements in the Model (Attwood 2006)

The model proposed by the author accounts for the fact that not all elements affect overall safety performance to the same degree. As such, the author gathered expert opinion in quantitative manner (survey questionnaire), from forty five offshore safety professionals. The experts were asked to rate relative importance of elements using a one (not very important at all) to ten (crucial) scale. This information was used in two topics:

- The relative importance of factors influencing the accident process (Strength values) and,
- The degrees to which external factors affect corporate decisions, and to which the corporate decisions in turn affect the direct accident process (Influence coefficients).

The accident frequency prediction process requires the model run in two distinct modes. First, a calibration run is executed, where known accident rates are used to determine base case component reliabilities. Second, the model is run in predictive mode following adjustment of the base case reliabilities. The degree of adjustment is determined using a quantified comparison of safety conditions in the specific and base cases, which requires expert input from safety personnel familiar with both situations. In many applications, the global average safety situation is used as the base case. The overall visualization of the model is shown in Figure 3-8.

The model approach assumes a relatively constant failure rate model for the reliability calculation. This assumption is based on the trends of current statistical data such as fatal accident rate (FAR), injury rate (TRIR), among other safety indicators. Attwood (2006) states that the safety indicators (FAR, TRIR) have reached a relatively constant state, meaning events are occurring as a random process. The calculation of the system reliability starts with the calibration of the model. For this process global average data can be used in order to determine the reliability value of each one of the components of the network.

$$R(t) = \exp\left[-\int_0^t \lambda dt\right] = e^{-\lambda t}, t > 0$$

Where:

R= system reliability at time t

λ= average failure (accident) rate

Once the system reliability has been calculated, the expected number of accidents for a unit time (usually taken as one year) is calculated according to the reliability formula shown below:

$$\boxed{\lambda = -Ln(R)}$$

Assuming a constant failure rate, then, the Poisson distribution proposes the following equation to calculate the probability of "x" occurrences in a unit time (one year in this example).

$$\boxed{P_x = \frac{\lambda^x e^{-\lambda}}{x!}}$$

Where:

P_x= Probability of "x" occurrences

λ= Average or expected number of occurrences (that can be obtain from running the model)

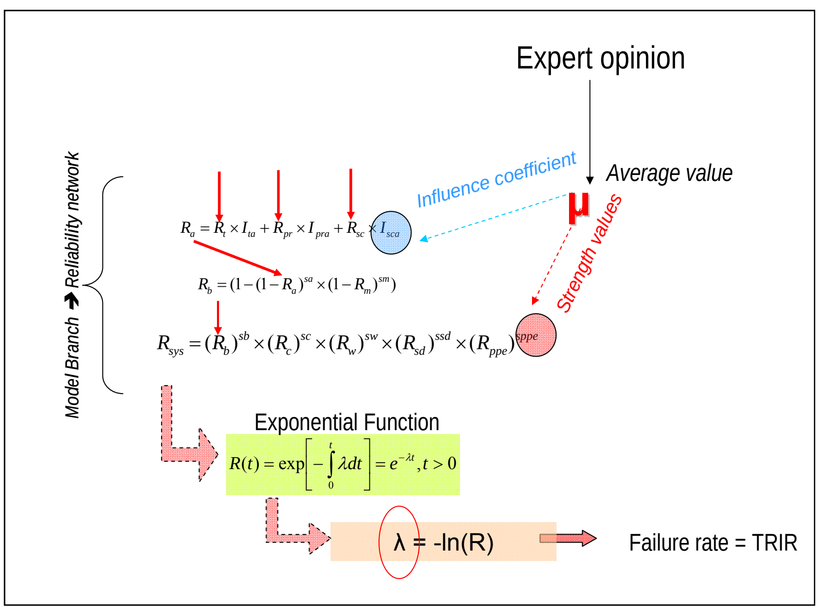


Figure 3-8 Visualization of the Model Inputs and Outputs

3.5.3.3 Conclusions

The model can be used by offshore oil and gas safety professionals in any of the following ways:

- To predict occupational accident frequency under any unique safety environment.
- To observe improvements in results achievable with changes in input conditions (either individual elements or groups). Thereby facilitating optimal management decisions. These changes can result from either change in asset status, or conscious adjustments in safety philosophy.
- To set realistic safety targets for minimizing overall risk.

3.5.4 Human Reliability Assessment During Offshore Emergency Conditions (Musharraf, Hassan et al. 2013)

3.5.4.1 Model Overview

Musharraf, Hassan et al. (2013) presented a quantitative approach to Human Reliability Analysis (HRA) during emergency conditions in an offshore environment. This research recognizes that most of the available HRA methodologies are based on expert judgment techniques due to the lack of human error data for emergency conditions. Nonetheless, expert judgment may introduce uncertainly and incompleteness which are usually not taken into account in the analysis. Thus, the objective of this research is to address the issue of handling uncertainty associated with expert judgment. This paper assesses the Human Error Probability (HEP) during different phases of an emergency using a Bayesian Network (BN) approach integrated with an evidence theory approach. As part of the validation, this methodology is compared with the analytical approach called: Success Likelihood Index Methodology (SLIM). Some advantages of this model are: the flexibility of updating new information as it becomes available, and the capacity of representing complex interactions.

3.5.4.2 Justification of the Approach

The assessment of Human reliability or Human Error Probability (HEP) is important in order to improve the design of more effective safety systems and emergency management systems. This research recognizes that there is a lack of human error data for emergency conditions. Therefore, most of the available HRA methodologies are based on expert judgment techniques.

Today, there are several Human Reliability Analysis (HRA) methods developed and used (Musharraf, Hassan et al. 2013). However, as identified by this research these HRA techniques have two very important limitations:

- First, they are unable to handle uncertainty and inconsistency associated with expert judgment.
- Second, the majority of these techniques assume unrealistic independence among human factors and associated actions.

Therefore the objective of this paper is to improve current HRA analysis by addressing these limitations. The methodology is developed and validated by assessing Human Error Probability (HEP) for offshore emergency situation.

The lack of real data for the analysis of human error makes necessary the inclusion of expert judgment to the analysis, examples of which are Success Likelihood Index Methodology (SLIM) and Technique for Human Error Rate Prediction (THERP) models. Expert judgment from a single expert may be biased and incomplete, and therefore insufficient or inappropriate for a reliable human error prediction. This research proposes the use of evidence theory to combine multi-expert knowledge and hence increase the reliability of human error prediction.

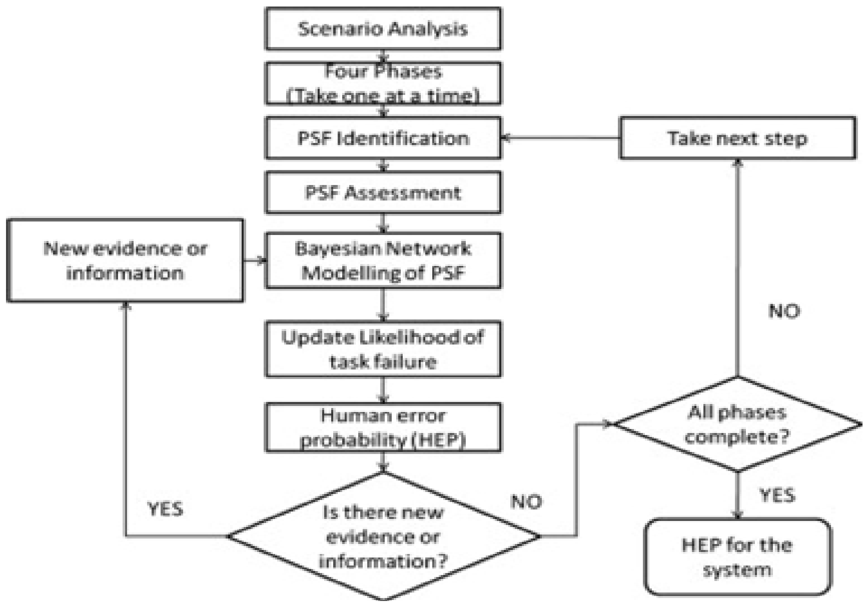


Figure 3-9 Methodology Flowchart (Adopted from Musharraf, Hassan et al. (2013)

The first step of Human Reliability Assessment as proposed by this paper is to focus on human behavior and identify a set of human factors believed to be related to the worker performance. These factors are called the human Performance Shaping Factors (PSFs). This research states that, the conditions or circumstances under which an event occurs are influenced by underlying dependency and contextual factors. In addition, the tasks performed in an emergency scenario (such as in an offshore emergency situation) are interdependent and have relations that must be taken into consideration. Individuals have to perform a sequence of tasks and the outcome of one task generally affects the task that follows.

Therefore, BN is used to represent the relationships among human factors and associated actions in a hierarchical structure. The network represents external relations of PSFs and associated actions, rather than internal dependencies among PSFs themselves. An advantage of the model is that the network enables dynamic updating through emerging information.

The methodology starts with the scenario analysis. At the end of this step the scenario is divided into smaller phases. A total of 17 tasks were identified that are broken down into four muster phases:

Table 3-5 Muster Action Broken Down by Muster Phase (Table Constructed From Work of Musharraf, Hassan et al. (2013)

Master phases	Tasks
Awareness phase	1) detect alarm 2) identified alarm 3) act accordingly
Evaluation phase	4) Ascertain if danger is imminent 5) Muster if in imminent danger 6) Return process equipment to safe state 7) Make workplace as safe as possible in limited time
Egress phase	8) Listen and follow PA 9) Evaluate potential egress paths and choose route 10) Move along egress route 11) Assess quality of egress route while moving to TSR 12) Choose alternate route if egress path is not tenable 13) Assist others if needed or as directed
Recovery phase	14) Register at TSR 15) Provide pertinent feedback attained while en-route to TSR 16) Don personal survival suit or TSR survival suit if instructed to abandon 17) Follow OIM instructions

Then for each phase listed above, PSFs influencing human performance are identified. For example, in the awareness phase, the skills required to detect the alarm, identify the alarm and act accordingly are listed and from that list specific PSF are identified.

An example of the identification of PSF for the task "detect alarm" is as follows:

Table 3-6 Example of the Identification of PSF for the Task "Detect Alarm"

Task/Action	Skill Required	Identified PSF
Detect alarm	1) Concentration 2) Perception	Distraction, stress Distraction (noise), physical condition

The prior knowledge of each PSF comes from different expert sources in terms of basic probability assignments and they are combined using evidence theory (DST). Using the same process, the prior probabilities of each PSF of the model are obtained. With the support of causal dependency in each phase and the probabilities obtained in the PSF assessment stage, BNs are developed for each task. BNs are updated each time there is new information or evidence available. As a result, the likelihood of task failure and corresponding Human Error Probability (HEP) are finally calculated. This process is repeated for all phases identified during scenario analysis.

3.5.4.3 Conclusions

The research approach has proved to be simple and effective in assessing human error likelihood. In addition, the methodology provides the flexibility of dynamic updating the

BN with emerging evidence. Precise estimates of human error using this method could help to design more effective emergency management systems.

3.5.5 Comparison of the Described Relevant Models

A comparison of the four models has been carried out the results are presented in Table 3-7

Table 3-7 Comparison Table for Described Relevant Models

Model name	Approached used	Model capabilities	Advantages	Disadvantages
Modeling Offshore safety focusing on human and organizational factors(HOs)	Combination of Swiss cheese for a generic assessment framework and Bayesian Network to build a causal relationship	* Calculation of the probability of a particular accident in the offshore industry. *Safety Assessment of the particular offshore installation.	*Considers the influence of human and organizational factors in the accident process *Introduces expert opinion which helps to update constantly the ever-changing environment of offshore installations *The Bayesian approach (probabilistic) helps to deal with the high level of uncertainty existing in the offshore industry.	*The model relies on expert opinion which is not always easy to have access to. *BN requires precise information in the form of prior and conditional probability tables often very difficult to obtain as numerical values.
Quantifying Occupational Risk model (ORM)	Bow-tie approach (combination of fault trees and event trees), plus barrier analysis to link storybuilder with bow-tie	*Quantitative analysis of risk. *Determination of dominant paths to accidents *Calculation of most cost effective method for risk reduction	*The model has a strong capability and flexibility to be adapted to various industries and different working conditions. *The model can estimate most cost effective approach for accident reduction. *The model uses a very well set of data collected for the government agencies. *The model is available for public domain. *The model has a probabilistic approach that helps to deal with the level of uncertainty related to the field.	*The model is run based on historical data of all accidents disregarding the industry of origin, as such predictability can be very coarse specially in particular scenarios such as offshore installations. *Very accurate data is required to link the story builder with the bow-tie model. "The state of the barrier that fail" and they were thought to be relevant are reported by the inspectors of safety. This information contains lots of uncertainty and in lots of cases has to be inferred.
Reliability base model for occupational accidents	Modified reliability network	*Prediction of occupational accident frequency * Determination of components that can improve the overall safety of the system	*The model has a holistic approach, considers the influence of societal factors, organizational factors and factors directly related with the overall system *Introduces expert opinion which helps to update constantly the ever-changing environment of offshore installations *The model is field specific design for offshore operations *The model it is relatively simple to	*The model relies strongly on expert opinion which is not always easy to have access to. *The model relies of the assumption of constant failure rates for the reliability calculation which is not always true. *The capability for prediction in a long term is limited * The accuracy of the prediction depends largely in expert opinion.

Model name	Approached used	Model capabilities	Advantages	Disadvantages
			understand and apply	*It uses a determinist approach increasing level of uncertainty
Human reliability assessment during offshore emergency conditions	Bayesian Network (BN) approach integrated with evidence theory approach.	*Prediction of Human error likelihood for a better design of emergency management systems.	*The model is relatively simple and effective for human error likelihood prediction. *The model represents the relation among internal human factors and associated actions. *The methodology is flexible and dynamic and capable of updating the BN with emerging evidence.	*The model relies on expert opinion which is not always easy to have access to. *BN requires precise information in the form of prior and conditional probability tables often very difficult to obtain as numerical values. *The model only takes internal human factors into account. External factors are not considered in the current model.

4 RESEARCH METHODOLGY

This research aims at defining a quantitative approach for the estimation of occupational risk for offshore operations using a probabilistic framework. Attwood (2006) developed a reliability model for the quantification of occupational accidents in the offshore oil and gas industry (accident frequency). Despite of its novelty, the model relies on deterministic parameters as input values. Therefore, to enhance the Reliability Based Model, the use of probabilistic inputs is proposed. The probabilistic approach subsequently lead to the development of an occupational risk model.

Probabilistic inputs would more realistically represent the uncertainty associated with the parameters used in the model. Monte Carlo simulations will be used as a tool to establish a probability distribution of output results. The output then can be converted into an incident rate value using central limit theorem. Once the consequences are determine and characterized, occupational accident risk will be calculated.

This chapter is divided in two parts. First, the original Reliability Model (quantitative deterministic approach) as proposed by Attwood (2006) is briefly described to have an understanding of the model. Second, the methodology proposed by this research for the modification of the Reliability Model (quantitative probabilistic approach) to improve and extend original model is presented.

4.1 The Reliability Model Proposed by Attwood (2006)

4.1.1 Model Overview, Justification, and Objectives

The "Reliability based model for occupational accident in the offshore oil and gas industry", developed by Daryl Attwood is a holistic quantitative model that covers the gap of quantitative models in the occupational accident risk in offshore process operations. The model uses a reliability approach and is capable of:

- predicting the likelihood of occupational accidents on an specific offshore platform,
- estimating accident rate within an industry sector and,
- providing the means to effectively direct resources deployment to produce optimal safety results.

The model considers three groups of factors (layers), which affect accident frequency: External Layer, Corporate Layer and Direct Layer. The approach is based on a chain of influence between the layers; originating with external factors, which act through corporate elements, to affect factors directly influencing the accident process (refer to Figure 3-6 and Section 3.5.3).

4.1.2 The Model Structure

World wide data (statistical data and graphical representation) of offshore occupational accidents were analyzed and studied by Attwood (2006), to confirm one of the model principles: the existence of corporate and regional differences in safety performance. Therefore, the model was structured as a three layer model as shown in Figure 3-6 (Refer to Section 3.5.3.1). The basic premise of the model is stated as:

"Occupational accidents result from an unsatisfactory direct interaction between worker and the workplace environment provided by an organization whose actions were, in turn influenced by external elements". Given the premises above, the model was structured considering the specific elements showed in Figure 4-1 and the relation between them.

<table>
<tr><th colspan="2">External Layer</th><th>Corporate Support Layer</th><th colspan="3">Direct Layer</th></tr>
<tr><td colspan="2">Value placed on life by society</td><td>Corporate safety culture</td><td colspan="2" rowspan="2">Individual behaviour</td><td>Attitude</td></tr>
<tr><td rowspan="3">Financial Drivers</td><td>Price of oil</td><td>Safety training programme</td><td>Motivation</td></tr>
<tr><td>Shareholder pressure</td><td>Safety procedures</td><td rowspan="5">Individual capability</td><td rowspan="2">Mental</td><td>Knowledge</td></tr>
<tr><td>Royalty regime</td><td rowspan="7"></td><td>Intelligence</td></tr>
<tr><td colspan="2" rowspan="6"></td><td rowspan="3">Physica l</td><td>Coordination</td></tr>
<tr><td>Fitness</td></tr>
<tr><td>Lack of fatigue</td></tr>
<tr><td colspan="3">Weather</td></tr>
<tr><td colspan="3">Safety design</td></tr>
<tr><td colspan="3">Personal Protective Equipment</td></tr>
</table>

Figure 4-1 Specific Elements of the Model (Adopted From Attwood, 2006)

4.1.3 Model Elements Description

The reliability model consist of specific elements divided in three layers or categories. The layers of the model are described as follows:

4.1.3.1 Direct Layer

The direct layer considers the factors directly affecting accident likelihood. These factors are: weather conditions, safety related design of the work place, quality of protective equipment and workers behavior and capabilities. The first three factors mentioned above are direct inputs to the model. However, worker behavior and capabilities factors require more detail analysis due to the complexity to express them numerically. Therefore, it has been subdivided in other categories as shown in Figure 4-2. The description of each of the specific elements considered for the model input is as follows:

- Weather conditions: average weather conditions at the work place.
- Safety related design of the work place: takes into account the type of facility (oil or gas) and related work environment.
- Quality of protective equipment (PPE): supplied by the company i.e. hat, boots, safety glasses, and earplugs.
- Attitude: can be defined using the statement that good safety attitudes will produce direct benefits and general improvement of overall corporate safety culture. Attitude can be positively influenced by the organization through encouragement and engagement.
- Motivation: to operate in a safe manner must be clearly provided by management and supervisors (corporate layer) trough means of positive reinforcement and penalties.

- Knowledge: component that comprises of the safety related information retained by the worker following training sessions.
- Intelligence: component that allows the worker to cope with safety issues not specifically covered by training and procedures.
- Coordination: reasonable degree to perform the task.
- Fitness: reasonable degree to perform the task.
- Lack of fatigue: reasonable degree to perform the task.

The specific elements consider for the model input, mentioned above are the ones in colour in Figure 4-2.

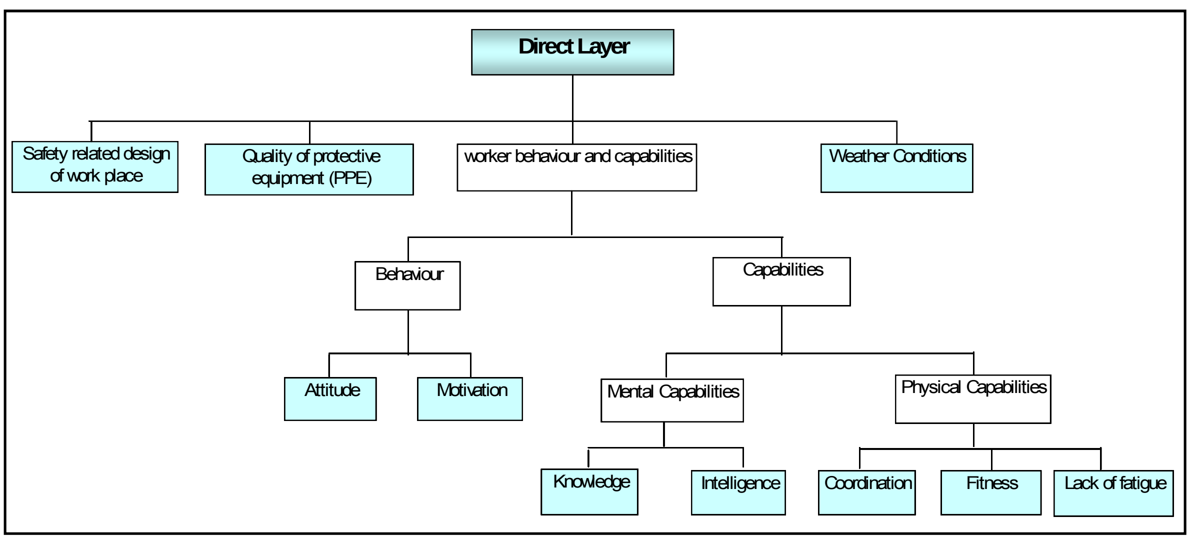


Figure 4-2 Elements Corresponding to the Direct Layer of the Model

4.1.3.2 Corporate Layer

The corporate layer is the safety related support provided by the organization. The factors considered in this layer are:

- Corporate safety culture: nurtured by the organization (difficult to quantify). Today offshore operators take many practical steps to ensure that the basic elements required for safe work activities are in place. These include the development of safety training programs and the distribution of safety procedures and guidance notes.
- Safety training: delivered to the staff; the author mentions that maintaining an appropriate balance in the intensity and quantity of training sessions and procedures has a crucial importance.
- Procedures: Offered to reduce accident risk.

4.1.3.3 External Layer

Attwood (2006) supports taking into account this factor since cultural expectations differ enormously throughout the world. As such, region-specific societal forces will affect corporate safety results in several ways. The factors considered in this layer are the value on human life and the financial drivers. As Figure 4-3 shows, the financial drivers' factor is subdivided into three other elements. The specific elements considered for the model input are the ones coloured in Figure 4-3.

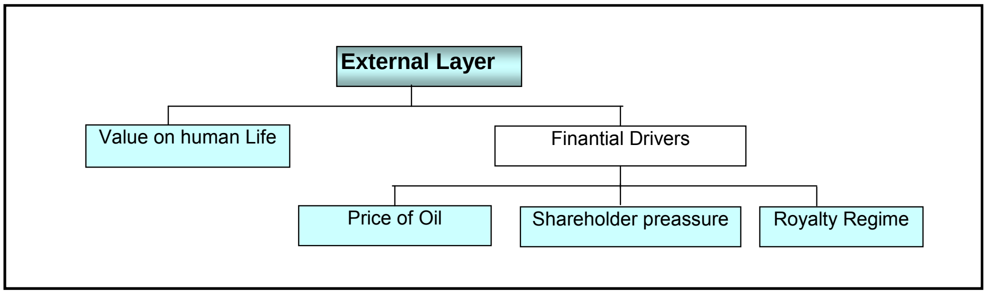


Figure 4-3 Elements Corresponding to the External Layer of the Model

The description of each of the specific elements considered for the model input is as follows:

- Value of human Life: this may vary considerably among different regions. Operators will receive through regulatory process, a relatively high pressure to impose strict safety programs in regions where human life has a higher value. The opposite relative effect will be found in regions where human life has comparatively lower societal value.

- Price of oil: Attwood (2006) found a strong inverse correlation between price of oil and accident frequency. This may be interpreted as when money is scarce there is an increase pressure on the quality of the safety programs enacted by the operators.

- Shareholder pressure: related to the degree to which an organization feels pressure from its ultimate owner to improve bottom line performance.

- Royalty regime: it is heavily region-specific. Strict royalty regimes erode project profitability which in turns may produce an undesirable negative effect in safety performance.

4.1.4 Structure of the Model

The accident process was modeled using a modified reliability network. Attwood's investigations lead to the recognition that there are several similarities between the components and interconnections of a mechanical/electrical engineering system. As such, the overall system is subdivided into sub-systems, where the arrangement of elements are either in series (i.e. weather, safety design and PPE) or parallel (i.e. the elements that comprise physical capability; coordination, fitness and lack of fatigue). The complete internal arrangement of the elements in the model is shown in Figure 3-7 (Section 3.5.3.2).

The model proposed by the author accounts for the fact that not all elements affect overall safety performance to the same degree. As such, Attwood (2006) gathered expert opinion in quantitative manner (survey questionnaire), from 45 offshore safety professionals (Appendix II). The experts were asked to rate relative importance of elements using a one (not very important at all) to then (crucial) scale. This information was used in two topics:

- The relative importance of factors influencing the accident process, and
- The degrees to which external factors affect corporate decisions, and to which the corporate decisions in turn affect the direct accident causation process.

The expert opinion approach was preferred over statistical data, as Attwood (2006) mentioned: "accident statistics may not as is usually assumed, be the best measure of corporate safety performance; this is essentially because, accidents remain relatively rare". As such, concluding that an organization that had one accident in a given year, compared with another organization that had two accidents in the same year; has a safety program that is twice as effective, will be questionable.

4.1.5 The Reliability Calculation

The system reliability is calculated as a function of the direct layer components' reliabilities. Therefore, if the direct element reliabilities are known, the overall system reliability can be calculated directly. The overall reliability can also be calculated using external or corporate component reliabilities. The equation of calculating system reliability is as follows:

$$R_{sys} = (R_b)^{sb} \times (R_c)^{sc} \times (R_w)^{sw} \times (R_{sd})^{ssd} \times (R_{ppe})^{sppe}$$

Where:

R_b = Reliability of behaviour sb = strength of behaviour

R_c = Reliability of capability sc = strength of capability

R_w = Reliability of weather sw = strength of weather

R_{sd}= Reliability of safety design sd = strength of safety design

R_{ppe} = Reliability of personal protect. Equip . $sppe$= strength of personal protect. Equip.

R_w (reliability value for weather conditions) is a ***direct input*** (i.e. it is an independent variable not base on the values of other elements). Reliabilities of the other elements are calculated as follows:

Reliability of Behavior:

$$R_b = (1 - (1 - R_a)^{sa} \times (1 - R_m)^{sm})$$

where:

sa = Strength of attitude

R_a= Reliability of attitude

R_m = Reliability of motivation

sm = Strength of motivation

Composed of:

$R_a =$ Reliability of attitude

$$R_a = R_t \times I_{ta} + R_{pr} \times I_{pra} + R_{sc} \times I_{sca}$$

R_m= Reliability of motivation

$$R_m = R_t \times I_{tm} + R_{pr} \times I_{prm} + R_{sc} \times I_{scm}$$

Where:

$R_{(t, pr, sc)}$ = Reliability of (training, safety procedures, safety culture)

$I_{(ta, pra, sca, tm, prm, scm)}$ = Influence coefficient of safety (training, procedures, culture) on attitude/motivation.

Reliability of Safety Training:

$$R_t = R_{po} \times I_{pot} + R_{sp} \times I_{spt} + R_{rr} \times I_{rrt} + R_{vl} \times I_{vlt}$$

Reliability of Safety Procedures:

$$R_{pr} = R_{po} \times I_{popr} + R_{sp} \times I_{sppr} + R_{rr} \times I_{rrpr} + R_{vl} \times I_{vlpr}$$

Reliability of Safety Culture:

$$R_{sc} = R_{po} \times I_{posc} + R_{sp} \times I_{spsc} + R_{rr} \times I_{rrsc} + R_{vl} \times I_{vlsc}$$

where:

$R_{(po, sp, rr, vl,)}$= Reliability of (price of oi, shareholder pressure, royalty regime, value of life); all of them ***direct input***.

$I_{(pot, spt, rrt, vlt)}$= Influence coefficient of (price of oil on, shareholder pressure, royalty regime, value of life) in safety training.

$I_{(popr,\ sppr,\ rrpr,\ vlpr)}$= Influence coefficient of (price of oil on, shareholder pressure, royalty regime, value of life)in safety procedures.

$I_{(posc,\ spsc,\ rrsc,\ vlsc)}$= Influence coefficient of (price of oil on, shareholder pressure, royalty regime, value of life) in safety culture

Reliability of Capability:

$$R_c = (R_p)^{sp} \times (R_{me})^{sme}$$

Composed of:

Reliability of physical capability:

$$R_p = (1-(1-Rf)^{sf} \times (1-R_{lf})^{slf} \times (1-R_c)^{sc})$$

Composed of:

Reliability of Fitness:

$$R_f = R_t \times I_{tf} + R_{pr} \times I_{prf} + R_{sc} \times I_{scf}$$

Reliability of lack of fatigue:

$$R_{lf} = R_t \times I_{tlf} + R_{pr} \times I_{prlf} + R_{sc} \times I_{sclf}$$

Reliability of coordination:

R_c= direct input

Where:

$I_{(tf,\ prf,\ scf,\ tlf,\ prlf,\ sclf,\ )}$= Influence coefficient of safety (training, procedures, culture) in fitness($_f$)/lack of fatigue($_{lf}$).

sp= Strength of physical capability

sme= strength of mental capability

sf= strength of fitness

slf= strength of lack of fatigue

sc= strength of coordination

Reliability of mental capability:

$$R_{me} = (1-(1-R_k)^{sk} \times (1-R_i)^{si})$$

Composed of:

Reliability of knowledge:

$$R_k = R_t \times I_{tk} + R_{pr} \times I_{prk} + R_{sc} \times I_{sck}$$

and

Intelligence:

R_i= direct input

Where:

$I_{(tk,\ prk,\ sck)}$= Influence coefficient of (safety training, safety procedures and safety culture) on knowledge.

sk= Strength of knowledge

si= Strength of intelligence

Reliability of safety design:

$$R_{sd} = R_t \times I_{tsd} + R_{pr} \times I_{prsd} + R_{sc} \times I_{scsd}$$

where:

$I_{(tsd,\ prsd,\ scsd)}$= Influence coefficient of (safety training, safety procedures and safety culture) on safety design

Reliability of PPE:

$$R_{ppe} = R_t \times I_{tppe} + R_{pr} \times I_{prppe} + R_{sc} \times I_{scppe}$$

where:

$I_{(tppe,\ prppe,\ scppe)}$= Influence coefficient of (safety training, safety procedures and safety culture) on PPE

The complete model can be visualized in Figure 4-4 presented below

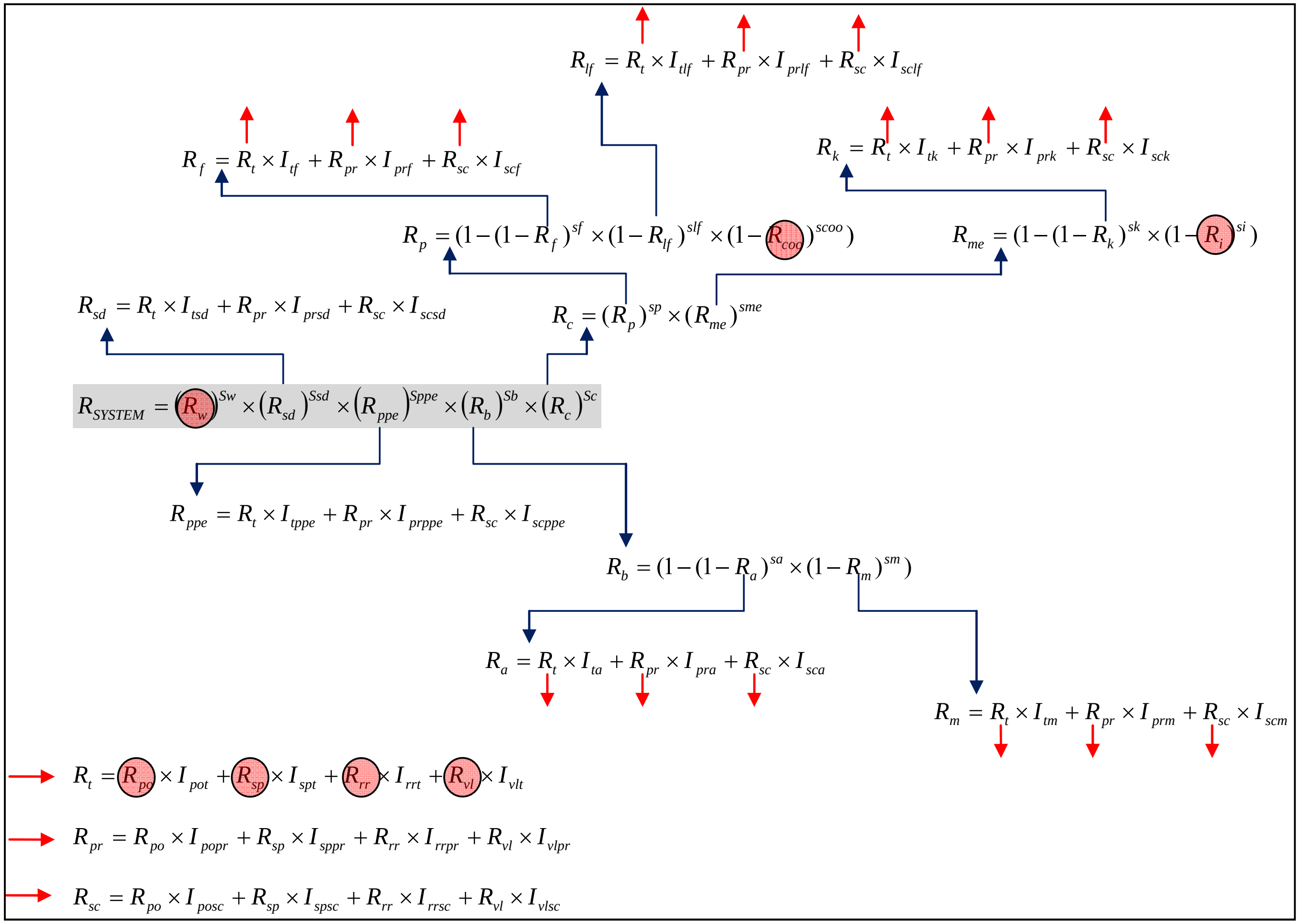


Figure 4-4 Visualization of the Model (Reliability Values Encircled in Red Correspond to Direct Input Values)

Summarizing, each main element's reliability is the sum of the products of the reliability and the associated influencing coefficient of those sub elements considered to have an influence on the main element.

4.1.5.1 Strength values (Strength of individual elements)

The strength values are obtained from the data gathered using questioners from worldwide offshore safety professionals (Total of 45 experts were consulted by Attwood). These questioners were used to quantify the effect (strength) of various factors thought to affect accident frequency. These values are based on the fact that the model accounts that not all elements of the model affect overall safety performance in the same degree.

The strength values are associated to the importance of all subgroups and individual elements within the model's "direct layer" only.

Table 4-1 Strength Values of Elements of the Direct Layer (Attwood 2006)

Element	Strength Value	Element	Strength Value
Main Elements		Capability	
Behavioral	0.25	Mental	0.64
Capability	0.21	Physical	0.36
Weather	0.15	Mental Capability	
Safety Design	0.21	Knowledge	0.54
PPE	0.18	Intelligence	0.46
Behavioral		Physical Capability	
Attitude	0.49	Coordination	0.33
Motivation	0.51	Fitness	0.29
		Lack of fatigue	0.38

The expert opinions were ranked using a common scale of 1 to 10, where 1 is not very important and 10 will mean crucial. It was necessary to normalize the average value of the gathered data, to represent clearly the relative importance of each element within its corresponding group or layer (refer to Table 4-1 and Appendix II). Therefore, as a result the sum of the entire relative element's importance of a specific group (layer) should be one. In the system reliability equation, the strength values are included in the model as the exponents (see Figure 4-4).

4.1.5.2 Influence Coefficients

The model philosophy proposes that external elements affect corporate decisions and actions and this in turn influence items which directly affect the accident process (Attwood, 2006). The inter-layer of influence has been accounted for in the calculations, using an approach of "matrices of influence coefficients". These matrices have been developed using expert survey questioner. As an example: Table 4-2 shows the influence of the elements of the external layer (value placed on life, price of oil, share holder pressure and royalty regime) over training procedures and safety culture.

Table 4-2 Influence Coefficients (Adopted from Attwood 2006)

External – Corporate Influencing Coefficients			
	Normalized Scores		
	Training	Procedures	Safety Culture
Value placed on life	0.43	0.43	0.44
Price of oil	0.18	0.19	0.18
Share holder pressure	0.27	0.26	0.25
Royalty regime	0.12	0.12	0.12

As mentioned earlier, the influence coefficients represent the degree of influence of the higher layers, for example in Table 4-2 among the four elements of the higher level. The element of value placed on life has the higher influence on training (about 43%). On the contrary royalty regime has the lower influence (about 12%). However, three of the direct elements: intelligence, coordination, and weather are considered to be independent variables (they do not respond to the influence of other layers) and require direct input (see seven independent elements in Figure 4-4, Section 4.1.5).

4.1.5.3 Calculation of Model Outcome-Expected Number of Accidents

The Attwood (2006) modeling approach considered constant failure rate model for the reliability calculation. The data that Attwood (2006) used for the offshore industry accident rate calculation was assumed to have reached a relatively constant state. Figure 4-5, shows one of the safety performance indicators; FAR – Fatal accident rate with respect to time. The dashed red lines show the portions he considered constant failure rates.

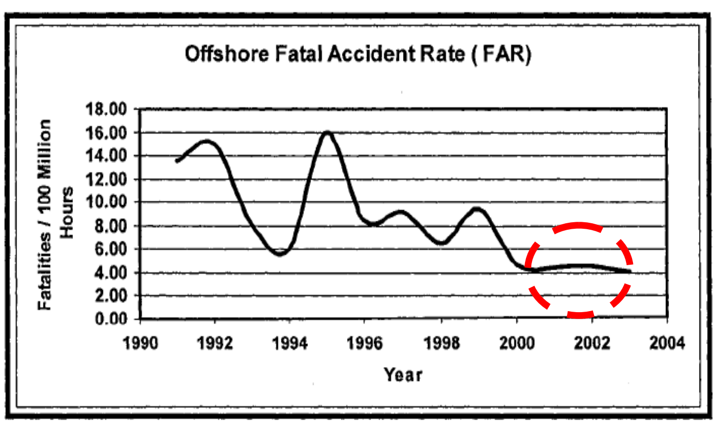


Figure 4-5 Oil and Gas Fatal Accident Rate versus Time (Attwood 2006)

Once system reliability was calculated, the expected number of accidents for a unit time (usually taken as one year) was calculated by Attwood (2006) according to the reliability formula shown below:

$$R(t) = \exp\left[-\int_0^t \lambda dt \right] = e^{-\lambda t}, t > 0$$

Where:

R= system reliability at time t

λ= average failure (accident) rate

Therefore, taking natural logarithms of both sides and setting t=1 the failure rate is calculated as follows:

$$\lambda = -Ln(R)$$

It is important to mention that usually the failure rates are obtained after a calibration process where equal base case reliabilities are assigned to all components. Attwood (2006) mentioned that the establishment of different component reliabilities at calibration would be an unnecessary complication to the process. The previous statement was supported by the author indicating that the model requires a comparison of specific case to a base case, not absolute reliability values. In other words, "absolute individual component reliabilities are not as important as the percentage of changes in them". However, this statement will be reviewed and modified for the probabilistic approach of the Reliability Model. The Modification will be presented later herein.

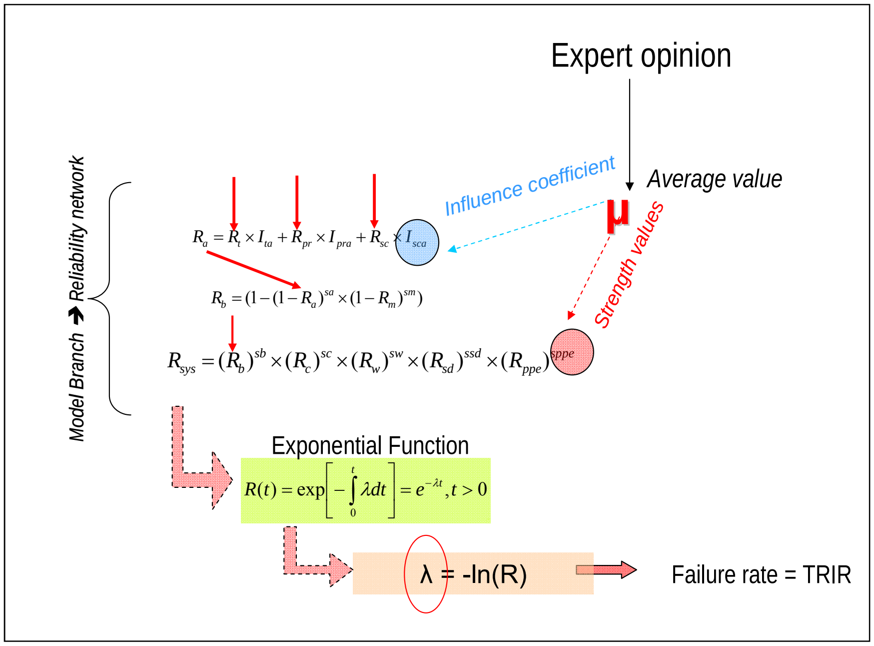


Figure 4-6 Visualization of the Model Inputs and Outputs – Schematic Visualized From the Method Proposed by Attwood (2006)

4.1.6 Model Calibration

To predict accident frequency, the model requires to be run in two distinct modes. First, a calibration run is executed, where known accident rates are used to determine base case component reliabilities. Second, the model is run in predictive mode following adjustment of the base component reliabilities in order to apply to a specific case. The adjustment requires expert input familiarized with both situations. In many applications the global average safety situation, with documented results is used as the base case.

4.2 The Proposed Probabilistic Occupational Accident Risk Model

Specific data such as POB (number of person on board) of a specific platform, and model components' reliability adjustment that is given by an expert panel for a particular platform are fundamental to run a particular case study. Three case studies were presented earlier by Attwood (2006): the Nova Scotia case study, the Newfoundland production installation, and the Gulf of Mexico drilling sector. All three cases were considered for this research. New additional Newfoundland occupational accident data were retrieved from public domain. Therefore, the Newfoundland case has been selected for the implementation of the probabilistic approach.

Table 4-3 Component Ratings for Newfoundland Installation (Attwood 2006)

Factor	Expert Score	Factor	Expert Score
External factors		**Direct factors**	
		Attitude	6
Value placed on life	9	Motivation	7
Price of oil	10	Lack of fatigue	8
Shareholder pressure	3	Coordination	5
Royalty regime	4	Fitness	6
Corporate factors		Knowledge	8
Safety culture	8	Intelligence	5
Safety training	7	Safety design	7
Safety procedures	9	Weather	1
		Personal protective equipment	9

Table 4-3 shows the scores assigned to model components by the expert panel for the Newfoundland Installation (Attwood 2006). This information is crucial for adjusting component reliabilities, from the base case to the location specific case, as explained in Section 4.1.5.1. The proposed modifications to the Reliability Model is graphically presented in Figure 4-7.

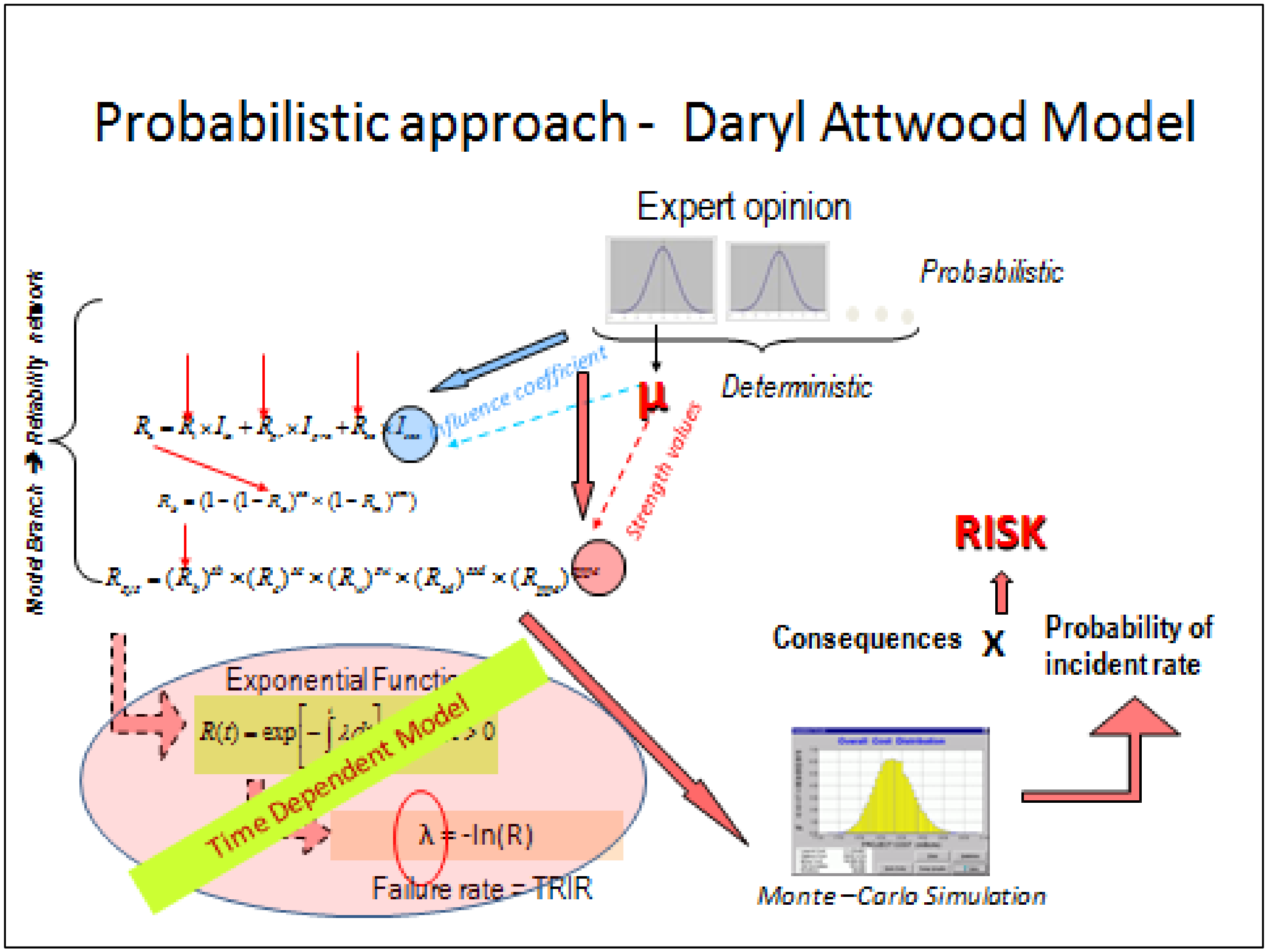


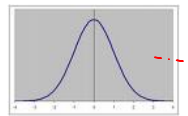
Figure 4-7 Summarized Visualization of the Probabilistic Approach of the Reliability Model Proposed by this Research

The modifications of the model involve more details than the ones presented in Figure 4-7. Therefore, a step by step model modification overview has been developed and it is schematically presented below. The model overview is divided in five tasks. Each task is then further developed and explained in detail in the following sections.

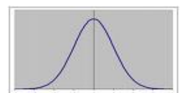
<u>Task 1</u>: Transforming expert opinion (strength values and influence coefficients) into a probabilistic input (normal distributions) for the calibration of the reliability model. This is an additional step to the Attwood model in terms of considering probabilistic distribution of parameters.

The diagrams below show the steps for the transformation of normalized expert opinion (in this case strength values) into normal distributions to feed into the proposed reliability model for calibration.

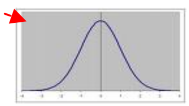
Element	Strength Value	Element	Strength Value
Main Elements		Capability	
Behavioral	0.25	Mental	0.64
Capability	0.21	Physical	0.36
Weather	0.15	Mental Capability	
Safety Design	0.21	Knowledge	0.54
PPE	0.18	Intelligence	0.46
Behavioral		Physical Capability	
Attitud	0.49	Coordination	0.33
Motivation	0.51	Fitness	0.29
		Lack of fatigue	0.38



N(μ_m, σ_m)



N(μp, σ_p)



N(μ_m, σ_m)

$$R_a = R_t \times I_{ta} + R_{pr} \times I_{pra} + R_{sc} \times I_{sca}$$

$$R_b = (1-(1-R_a)^{sa} \times (1-R_m)^{sm})$$

$$R_{sys} = (R_b)^{sb} \times (R_c)^{sc} \times (R_w)^{sw} \times (R_{sd})^{ssd} \times (R_{ppe})^{spp}$$

Reliability Model

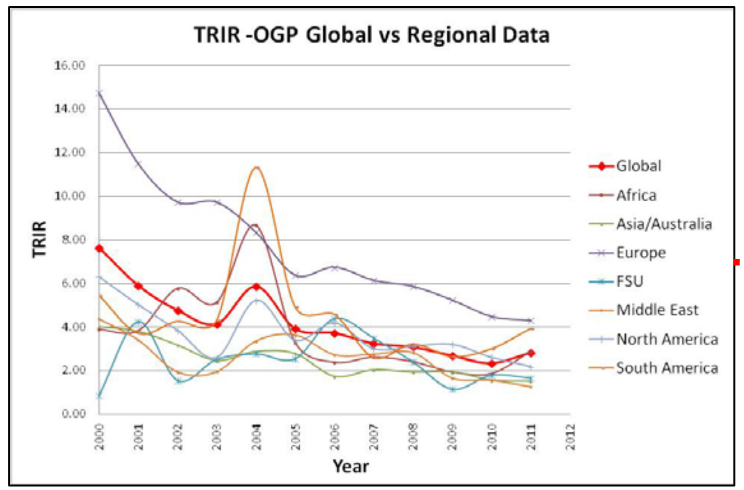
<u>Task 2:</u> Gathering TRIR data (from 2000 to 2011) and transforming these data into falure rate data and then reliability data for model calibration. This step is also another modification to the Attwood model.

TRIR is obtained from "Appendix B" of OGP reports (years 2000 to 2012). OGP reports give data by regions (seven regions) and by company type (offshore and onshore) for all safety indicators. The offshore regional data was used to calculate the respective TRIR for offshore operations (company and contractors included). Results are presented in the following figure.

Appendix B
Data tables

Summary of data

Region	Type	Hours worked ('000s)	No. fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	Company Onshore	78,919	0	13	9	34	0.00	0.16	0.71
	Company Offshore	15,455	0	7	6	11	0.00	0.45	1.55
	Contractor Onshore	377,234	5	79	82	165	1.33	0.22	0.88
	Contractor Offshore	86,965	2	59	77	133	2.30	0.70	3.14
	Sub Total	**558,573**	**7**	**158**	**174**	**343**	**1.25**	**0.30**	**1.22**
Asia/ Australasia	Company Onshore	86,215	5	26	11	28	5.80	0.36	0.90
	Company Offshore	29,308	0	5	11	21	0.00	0.17	1.26



<u>Task 2 (Cont'):</u>

The Process of obtaining the reliability values required for calibration of the proposed model is shown in the table below:

TRIR per 10^6 hours worked (from global data). These calculation are done for all 7 regions

=438300*(OGP data/10^6)

Year	Global OGP Data	Person-hours worked NL platform	Expected N° of Recordable Cases for NL	Failure probab. of a worker/year	Cumulative Failure (F)	Reliability (1-F)
2000	7.64	438300	3.349	0.033	0.033	0.967
2001	5.90	438300	2.587	0.026	0.059	0.941
2002	4.78	438300	2.094	0.021	0.080	0.920
2003	4.15	438300	1.819	0.018	0.098	0.902
2004	5.87	438300	2.574	0.026	0.124	0.876
2005	3.93	438300	1.721	0.017	0.141	0.859
2006	3.73	438300	1.636	0.016	0.157	0.843
2007	3.26	438300	1.428	0.014	0.172	0.828
2008	3.09	438300	1.354	0.014	0.185	0.815
2009	2.70	438300	1.183	0.012	0.197	0.803
2010	2.35	438300	1.030	0.010	0.207	0.793
2011	2.83	438300	1.240	0.012	0.220	0.780

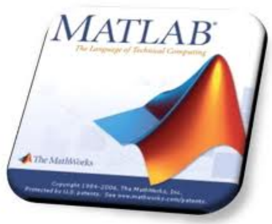
Assumptions:
100 people working in NL platform
50 people working in a given time (2 turns of 12 hrs each)
50*24*325.25 = 438,300

= (Expected No of Recordable cases for NL for the particular year) /100 (No of workers in a platform)

<u>Task 3:</u> Model Calibration is performed using reliability values found for the 7 regions (OGP data), to find the 7 unkowns. This is completely a new step and an extension to the Attwood model.

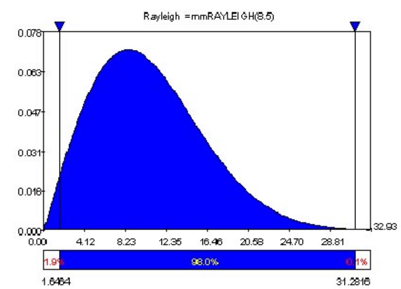
Seven Regions are:

Africa
Asia/Australia
Europe
FSU
Middle East,
North America and
South America



As a result the following results are obtained ("R" stands for reliability):

$R_{\text{Human Life}}$
$R_{\text{price of oil}}$
$R_{\text{Share holder pressure}}$
$R_{\text{royalty regime}}$
R_{weather}
$R_{\text{intelligence}}$
$R_{\text{coordination}}$



Each of the seven based reliability values(R) are expressed as a two parameter Weibull distribution.

Task 4: The estimated reliability values of the elements of the model are transformed for the Newfoundland platform case. All data is entered in the proposed reliability model and a Monte Carlo simulation is run using @RISK and the expert's score given for the platform. This is another major modification to the Attwoods (2006) approach.

The model is run using a new component reliability adjustment, different to Attwood's approach (2006, pp194 to pp195). The table below shows the transformation factor been used.

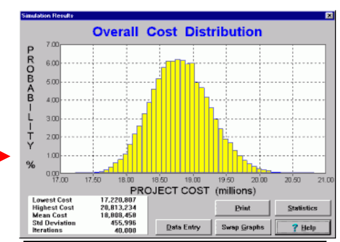
Factor	NFLD	Factor	Exponent
Value placed on life	9	Value placed on life	0.2
Price of oil	10	Price of oil	0
Shareholder pressure	3	Shareholder pressure	1.4
Royalty regime	4	Royalty regime	1.2
Safety culture	8	Safety culture	0.40
Safety training	7	Safety training	0.60
Safety procedures	9	Safety procedures	0.20
Attitude	6	Attitude	0.8
Motivation	7	Motivation	0.6
Lack of fatigue	8	Lack of fatigue	0.4
Coordination	5	Coordination	1
Fitness	6	Fitness	0.8
Knowledge	8	Knowledge	0.4
Intelligence	5	Intelligence	1
Safety design	7	Safety design	0.6
Weather	1	Weather	1.8
PPE	9	PPE	0.2

Experts' assigned scores for Newfoundland Platform

((10-Expert Score)/5)

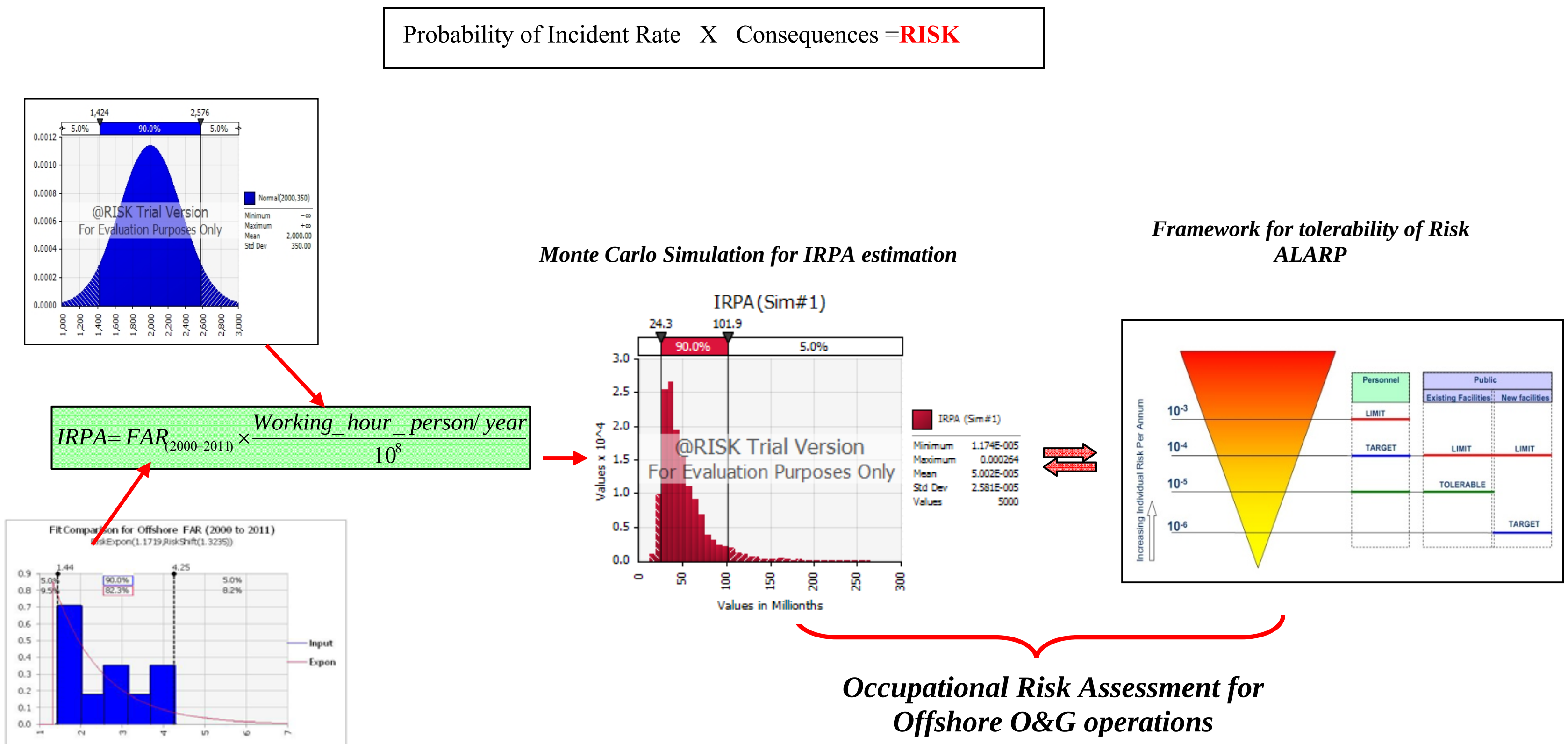
(R^Exponent)

Monte-Carlo Simulation



R of Newfoundland platform

<u>Task 5:</u> Risk calculation for the case study. Usually calculated and presented in terms of Individual Risk Per Annum (IRPA). This is another major extension to the Attwood work.



5 RESULTS AND DISCUSIONS

5.1 Task 1: Transforming Expert Opinion to a Probabilistic Input

Attwood (2006) gathered expert opinion in a quantitative manner (survey questionnaire), from 45 offshore safety professionals (Appendix II). The experts were asked to rate relative importance of the model elements using a 1 (not very important at all) to 10 (crucial) scale. This information was used in two topics:

- The relative importance of factors influencing the accident process (Table 4-1); and
- The degrees to which external factors affect corporate decisions, and to which the corporate decisions in turn affect the direct accident process (Table 4-2).

As described in Section 4.1.5, these data were used for the calculation of the "Strength Values" and "Influence Coefficients", respectively, in the reliability model. Attwood (2006) used the normalized average values (deterministic approach) for the expert's opinion as a model input. Attwood's proposed model was developed in an Excel spreadsheet with a predetermined number of input parameters and a few equations that use those input values to give a set of outputs (or response variables). This type of model is qualified as deterministic, given that the results are always the same no matter how many times it is re-calculated.

To transform the determinist model to a probabilistic one, the average values of the expert opinion have to be replaced by a "function" that describe the experts' responses. To achieve this objective; the normalized strength values and influence coefficients are transformed to normal distributions as input values for the reliability calculations. The selection of a normal distribution as the function that describes expert opinion is due to a main property of this distribution that fit the characteristics of the gathered data. Most of the expert opinion is near the middle datum or average of the sample. Figure 5-1 schematically shows the difference between the deterministic and the probabilistic approaches for this case. Tables Table 5-1 and Table 5-2 show the results of the probabilistic inputs.

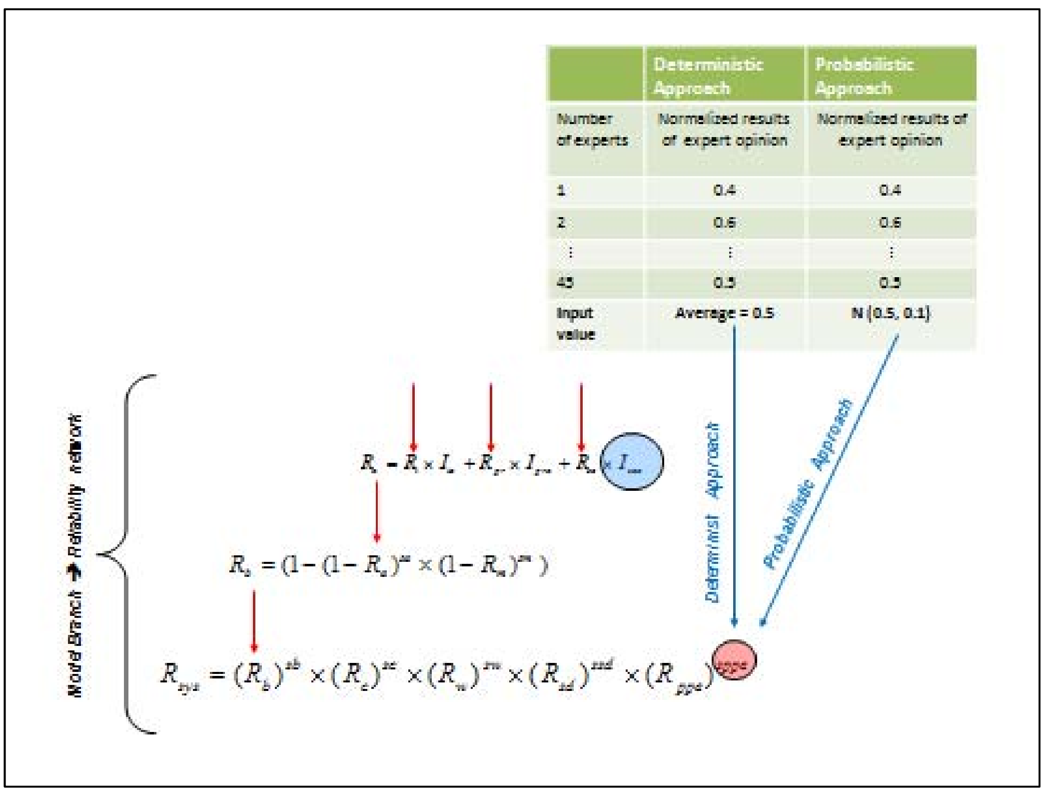


Figure 5-1 Graphical Representation of the Differences Between Deterministic and Probabilistic Input for the Reliability Model

Table 5-1 Normal Distribution Parameters for the Influence Coefficient

Influence Coefficients		Average	Standard Deviation
Training	Value place on life	0.43	0.08
	Price of oil	0.18	0.07
	Shareholder pressure	0.27	0.06
	Royalty regime	0.12	0.05
Procedures	Value place on life	0.43	0.10
	Price of oil	0.19	0.07
	Shareholder pressure	0.26	0.07
	Royalty regime	0.12	0.07
Safety culture	Value place on life	0.44	0.11
	Price of oil	0.18	0.06
	Shareholder pressure	0.25	0.08
	Royalty regime	0.13	0.06
Attitude	Training	0.33	0.04
	Procedures	0.30	0.04
	Safety culture	0.37	0.05
Motivation	Training	0.33	0.05
	Procedures	0.30	0.05
	Safety culture	0.37	0.06
Fitness	Training	0.34	0.06
	Procedures	0.30	0.04
	Safety culture	0.36	0.07
Lack of fatigue	Training	0.31	0.07
	procedures	0.32	0.06
	safety culture	0.37	0.08
Knowledge	Training	0.36	0.04
	Procedures	0.30	0.05
	Safety culture	0.34	0.04
Safety design	Training	0.31	0.05
	Procedures	0.32	0.06
	Safety culture	0.37	0.08
PPE	Training	0.32	0.07
	Procedures	0.33	0.04
	Safety culture	0.35	0.05

Table 5-2 Normal Distributions Parameters for the Strength Values

Strength Values		Average	Standard Deviation
Overall layer	External	0.22	0.09
	Corporate	0.42	0.08
	Direct	0.35	0.09
External Elements	Financial	0.43	0.15
	Value Placed on Life	0.57	0.15
Financial Elements	Price of Oil	0.30	0.12
	Shareholder pressure	0.44	0.14
	Royalty regime	0.26	0.11
Corporate layer	Safety Culture	0.35	0.05
	Training	0.33	0.03
	Safety Procedures	0.32	0.05
Direct layer	Behavioural	0.25	0.04
	Capability	0.21	0.03
	Weather	0.15	0.04
	Safety design	0.21	0.04
	PPE	0.18	0.05
Behavioural elements	Attitude	0.49	0.14
	Motivation	0.51	0.14
Capability elements	Physical	0.35	0.13
	Mental	0.65	0.13
Physical Capability	Lack of fatigue	0.38	0.05
	Coordination	0.33	0.04
	Fitness	0.29	0.05
Mental Capability	Knowledge	0.54	0.08
	Intelligence	0.46	0.08

5.2 Task 2: Gathering Global Data to Define Failure Rate for Model Calibration

5.2.1 The international Association of Oil and Gas Producers (OGP) Data

The International Association of Oil and Gas Producers (OGP), represents the upstream oil & gas industry, including the International Maritime Organization, the United Nations Environment Program (UNEP), Regional Seas Conventions and other groups under the UN umbrella (OGP 2013). OGP encompasses most of the world's leading publicly-traded, private and state-owned oil & gas companies, oil & gas associations and major upstream service companies. OGP members produce more than half the world's oil and about one third of its gas(OGP 2013). An essential part of OGP's mission is to represent the interests of the upstream industry before international regulators and legislators.

As one of its many functions OGP has been collecting safety incident data from member companies globally since 1985. The data collected are entered into the OGP safety database, which is the largest database of safety performance in the Exploration and Production (E&P) industry.

The principal purpose of the data collection and analysis is to record the global safety performance of the contributing OGP member companies, each year. The annual reports provide trend analysis, benchmarking and the identification of areas and activities on which efforts should be focused to bring about the greatest improvements in performance. The OGP incident reporting system covers worldwide exploration and production operations; both onshore and offshore, and includes incidents involving both; member companies and their contractor employees.

The key safety performance indicators presented in OGP annual reports are: number of fatalities, fatal accident rate, lost time injury frequency, restricted work day cases, loss time injury frequency and total recordable injury rate.

In this research, the safety performance indicator used for the proposed reliability model that better describes safety of offshore platforms is the Total Recordable Injury Rate (TRIR). The TRIR describes the number of recordable injuries (fatalities + lost work day cases + restricted work day cases + medical treatment cases) per 1,000,000 hours worked. This safety indicator was selected based on the project scope; because the TRIR better encompasses the occupational accidents that Attwood (2006) was aiming to describe: "occupational accidents of high frequency and low severity".

Twelve OGP Safety Performance reports (from 2000 to 2012) were reviewed to extract the data corresponding to the TRIR indicator for offshore activities (company and contractor included). The offshore data was gathered by year and by region in tables presented in the Appendix I of this thesis. These data were used to calculate the offshore TRIR for each year and for each region. Next, the TRIR calculated values were used as input values for the proposed reliability model in order to perform model calibration as described in Task 3 of the Methodology section. Figure 5-2 shows the summary of TRIR from 2000 to 2011.

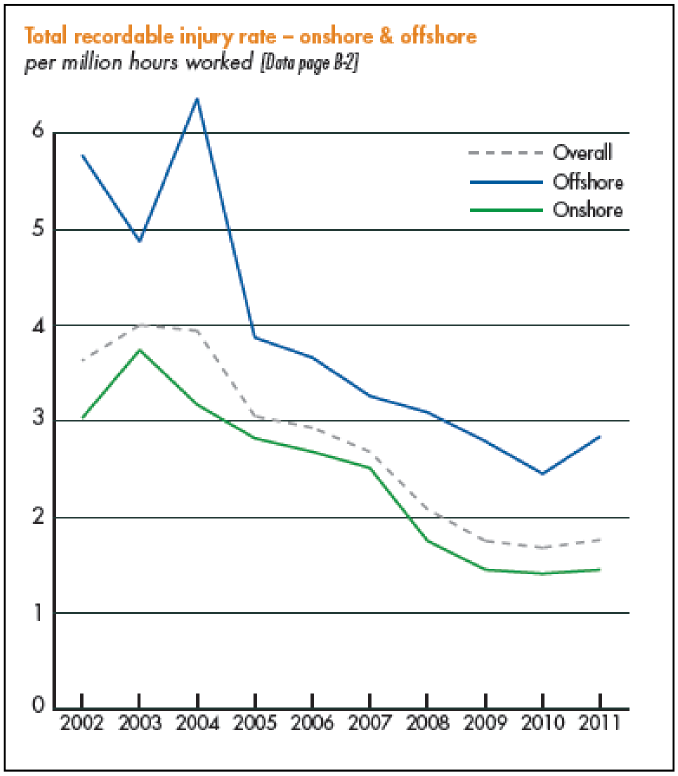


Figure 5-2 Total Recordable Injury Rate years 2002 to 2011 (Taken from OGP Data)

5.2.2 Modification of Model Calibration

The original methodology proposed by Attwood (2006) for the model calibration has been modified in this research. The bases for the modifications and the details are described below.

In the calibration proposed by Attwood (2006) the input values to the model are those components which are independent of others (higher level). This highest level elements are the four elements of the external layer (value of human life, price of oil, shareholder pressure and royalty regime), plus those elements of direct input (weather, intelligence and coordination). Attwood (2006) stated that there was no basis for setting these seven elements as input values different from each other, given the global average nature of the calibration run. However, during the course of this research it was found that if we assume that all this seven elements are the same (model with one variable instead of seven), the model does not calibrate. As an exercise, different values were replaced in the equation presented in Figure 4-4 (Section 4.1.5) it was evident that the model did not calibrate under those initial conditions. To demonstrate this through a simple example, let's assume that the reliability input values of the seven independent variables (R_{po}, $R_{sp,}$ R_{rr}, R_{vl}, R_{w}, R_{coo}, and $R_{i)}$ presented in the model are 1 (refer to Figure 4-4 reliability values circled in red). As a result, the next layers of the model influenced by the corporate layers (Rt, R_{pr}, $R_{sc)}$ will also be 1 given that the Influence Coefficients that are factoring each one of them are normalized and therefore add up to 1. Following the calculations, it is possible to see that also the elements of the direct layer such as R_b will also be 1 (note that the exponents are also normalized and they add to 1 in every layer). Therefore, as a result the overall R_{SYSTEM} is 1. Similarly, if the calculations are performed using other reliability value instead of 1 for the seven independent reliabilities input in the model, the overall result will be exactly the same as the input value. The reason why Attwood (2006) found calibration results apparently successful was because the model with one unknown or variable was solved using Goal seek function in Microsoft Excel environment and the output results were slight different than the input values. The input values were in the order of 10^{-5} or less. As such, Excel was rounding up the output results and therefore, there was a false impression of a proper calibration whereas the actual difference was due to arithmetic roundup of the calculated values.

As such, it was necessary to change the original framework of Attwood's model and assume that the seven elements have different input values. Therefore, in order to solve the seven unknowns for the calibration process it was necessary to find seven equations. Fortunately, the OGP data is also presented as segregated data for seven different regions of Africa, Asia/Australia, Europe, Former Soviet Union (FSU), Middle East, North America and South America. Therefore, these regional data were used to solve the calibration portion in MATLAB. The regional data used are summarized in Appendix I. The overall results are presented below in Table 5-3 and Figure 5-3

Table 5-3 TRIR Summarized Offshore OGP Database (Global and Regional Data, Years 2000 to 2011)

Year	Global	Africa	Asia/ Australia	Europe	FSU	Middle East	North America	South America
2000	7.64	3.90	4.03	14.75	0.86	4.37	6.31	5.47
2001	5.90	3.84	3.81	11.51	4.26	3.42	5.03	3.71
2002	4.78	5.78	3.18	9.74	1.56	1.95	3.85	4.28
2003	4.15	5.14	2.46	9.73	2.52	1.95	2.60	4.31
2004	5.87	8.68	2.88	8.35	2.78	3.36	5.23	11.34
2005	3.93	3.30	2.78	6.38	2.56	3.64	3.39	4.93
2006	3.73	2.39	1.73	6.75	4.40	2.73	4.19	4.59
2007	3.26	2.62	2.04	6.14	3.50	2.76	3.01	2.60
2008	3.09	2.41	1.92	5.87	2.41	2.83	3.12	3.22
2009	2.70	1.94	1.93	5.24	1.16	1.67	3.21	2.64
2010	2.35	1.87	1.56	4.48	1.80	1.56	2.60	3.01
2011	2.83	2.88	1.50	4.30	1.67	1.27	2.19	3.94

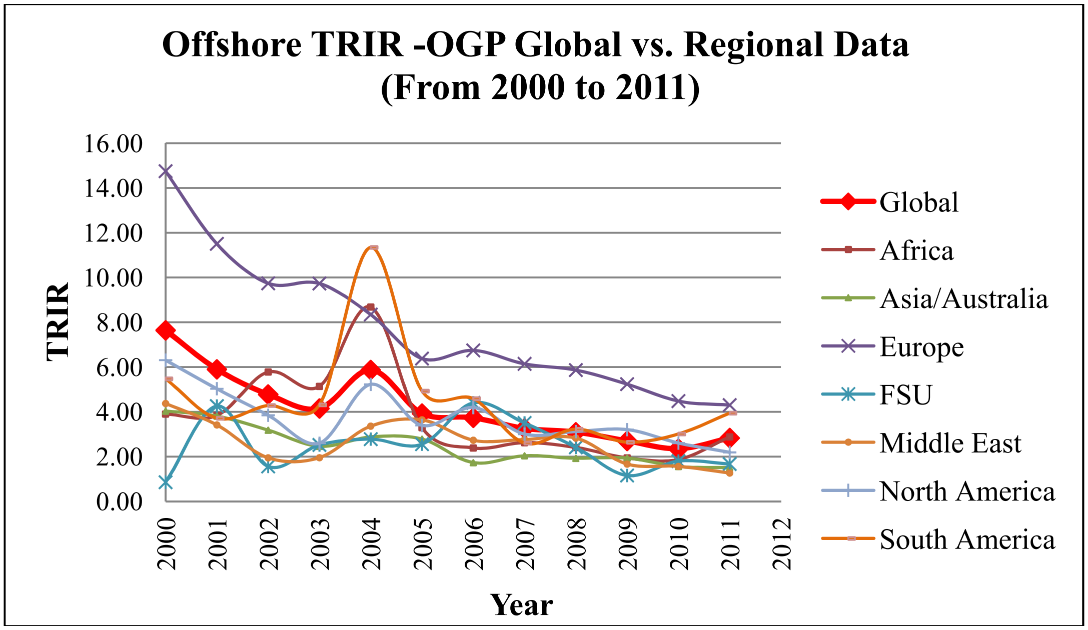


Figure 5-3 TRIR – Summarized Offshore OGP Database (Global versus Regional From 2000 to 2011)

The TRIR offshore regional data presented in Table 5-3 had to be transformed to reliability values, as explained in Task 2 (Methodology Section) in order to proceed with the calibration of the proposed reliability model. Those values are presented in Table 5-4.

Based on the conditions preset by Attwood (2006), it was assumed that the platform under study (Newfoundland offshore platform) has 100 workers and 50% of them are working continuously year around. Therefore, to calculate the TRIR for this particular platform using the global data the following transformation was done:

$$TRIR_{(NLplatform)} = 100 \times 12 \times 365.25 \times \left(\frac{TRIR_{(offshoredata)}}{10^6} \right)$$

Table 5-4 TRIR Transformed Data for 100 Workers in an Offshore Platform

Year	Global	Africa	Asia/ Australia	Europe	FSU	Middle East	North America	South America
2000	3.35	1.71	1.77	6.47	0.38	1.92	2.77	2.40
2001	2.59	1.68	1.67	5.04	1.87	1.50	2.21	1.63
2002	2.09	2.53	1.39	4.27	0.68	0.85	1.69	1.88
2003	1.82	2.25	1.08	4.27	1.11	0.86	1.14	1.89
2004	2.57	3.81	1.26	3.66	1.22	1.47	2.29	4.97
2005	1.72	1.44	1.22	2.80	1.12	1.60	1.49	2.16
2006	1.64	1.05	0.76	2.96	1.93	1.20	1.84	2.01
2007	1.43	1.15	0.89	2.69	1.54	1.21	1.32	1.14
2008	1.35	1.06	0.84	2.57	1.06	1.24	1.37	1.41
2009	1.18	0.85	0.85	2.30	0.51	0.73	1.41	1.16
2010	1.03	0.82	0.68	1.96	0.79	0.68	1.14	1.32
2011	1.24	1.26	0.66	1.89	0.73	0.56	0.96	1.73

The data in Table 5-4 had to be transformed into failure probability data, defined as the probability of an accident occurring to a worker of the NL offshore platform in one year of operation. Therefore, each TRIR presented in Table 5-4 had to be divided by 100 (platform population). The failure probability data is presented in Table 5-5.

Table 5-5 Calculated Worker Failure Probability Using TRIR (From Table 5-4)

Year	Global	Africa	Asia/ Australia	Europe	FSU	Middle East	North America	South America
2000	0.0335	0.0171	0.0177	0.0647	0.0038	0.0192	0.0277	0.0240
2001	0.0259	0.0168	0.0167	0.0504	0.0187	0.0150	0.0221	0.0163
2002	0.0209	0.0253	0.0139	0.0427	0.0068	0.0085	0.0169	0.0188
2003	0.0182	0.0225	0.0108	0.0427	0.0111	0.0086	0.0114	0.0189
2004	0.0257	0.0381	0.0126	0.0366	0.0122	0.0147	0.0229	0.0497
2005	0.0172	0.0144	0.0122	0.0280	0.0112	0.0160	0.0149	0.0216
2006	0.0164	0.0105	0.0076	0.0296	0.0193	0.0120	0.0184	0.0201
2007	0.0143	0.0115	0.0089	0.0269	0.0154	0.0121	0.0132	0.0114
2008	0.0135	0.0106	0.0084	0.0257	0.0106	0.0124	0.0137	0.0141
2009	0.0118	0.0085	0.0085	0.0230	0.0051	0.0073	0.0141	0.0116
2010	0.0103	0.0082	0.0068	0.0196	0.0079	0.0068	0.0114	0.0132
2011	0.0124	0.0126	0.0066	0.0189	0.0073	0.0056	0.0096	0.0173

The failure probability calculated for each year was transformed into cumulative failure, in order to calculate the reliability data. Reliability is defined as one minus the cumulative failure for the particular year under study. The cumulative failure calculation is presented in Table 5-6 and the calculated reliability values are presented in Table 5-7. Illustrations of the results are also presented in Figure 5-4 and Figure 5-5 respectively.

Table 5-6 Cumulative Worker Failure Probability Using TRIR (From Table 5-5)

Year	Global	Africa	Asia/ Australia	Europe	FSU	Middle East	North America	South America
2000	0.0335	0.0171	0.0177	0.0647	0.0038	0.0192	0.0277	0.0240
2001	0.0594	0.0339	0.0344	0.1151	0.0224	0.0341	0.0497	0.0403
2002	0.0803	0.0592	0.0483	0.1578	0.0293	0.0427	0.0666	0.0590
2003	0.0985	0.0818	0.0591	0.2005	0.0403	0.0512	0.0780	0.0779
2004	0.1242	0.1198	0.0717	0.2370	0.0525	0.0660	0.1009	0.1277
2005	0.1414	0.1342	0.0838	0.2650	0.0637	0.0819	0.1158	0.1492
2006	0.1578	0.1447	0.0914	0.2946	0.0830	0.0939	0.1342	0.1693
2007	0.1721	0.1562	0.1003	0.3215	0.0984	0.1060	0.1473	0.1808
2008	0.1856	0.1668	0.1088	0.3472	0.1089	0.1184	0.1610	0.1949
2009	0.1975	0.1753	0.1172	0.3702	0.1140	0.1257	0.1750	0.2065
2010	0.2078	0.1835	0.1241	0.3899	0.1219	0.1326	0.1865	0.2197
2011	0.2181	0.1916	0.1309	0.4095	0.1298	0.1394	0.1979	0.2328

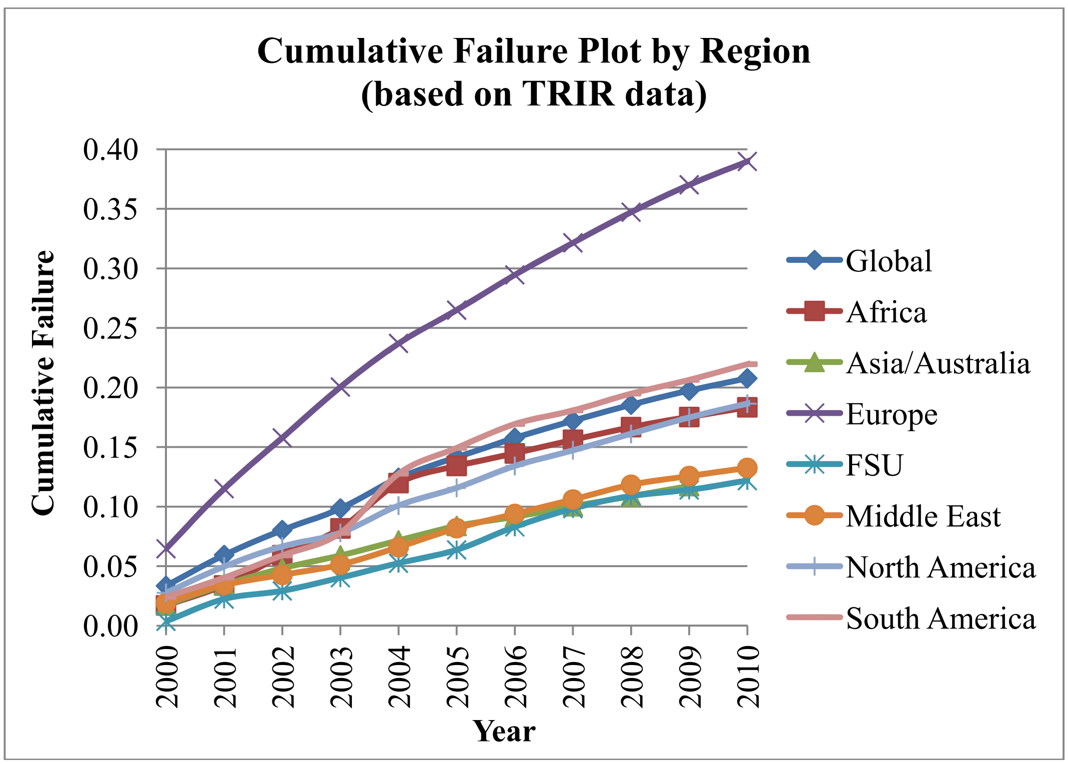


Figure 5-4 Cumulative Failure Plot by Region Based on the TRIR Data

Table 5-7 Reliability Based on Estimated Failure Probability Data.

Year	Global	Africa	Asia/ Australia	Europe	FSU	Middle East	North America	South America
2000	0.9665	0.9829	0.9823	0.9353	0.9962	0.9808	0.9723	0.9760
2001	0.9406	0.9661	0.9656	0.8849	0.9776	0.9659	0.9503	0.9597
2002	0.9197	0.9408	0.9517	0.8422	0.9707	0.9573	0.9334	0.9410
2003	0.9015	0.9182	0.9409	0.7995	0.9597	0.9488	0.9220	0.9221
2004	0.8758	0.8802	0.9283	0.7630	0.9475	0.9340	0.8991	0.8723
2005	0.8586	0.8658	0.9162	0.7350	0.9363	0.9181	0.8842	0.8508
2006	0.8422	0.8553	0.9086	0.7054	0.9170	0.9061	0.8658	0.8307
2007	0.8279	0.8438	0.8997	0.6785	0.9016	0.8940	0.8527	0.8192
2008	0.8144	0.8332	0.8912	0.6528	0.8911	0.8816	0.8390	0.8051
2009	0.8025	0.8247	0.8828	0.6298	0.8860	0.8743	0.8250	0.7935
2010	0.7922	0.8165	0.8759	0.6101	0.8781	0.8674	0.8135	0.7803
2011	0.7819	0.8084	0.8691	0.5905	0.8702	0.8606	0.8021	0.7672

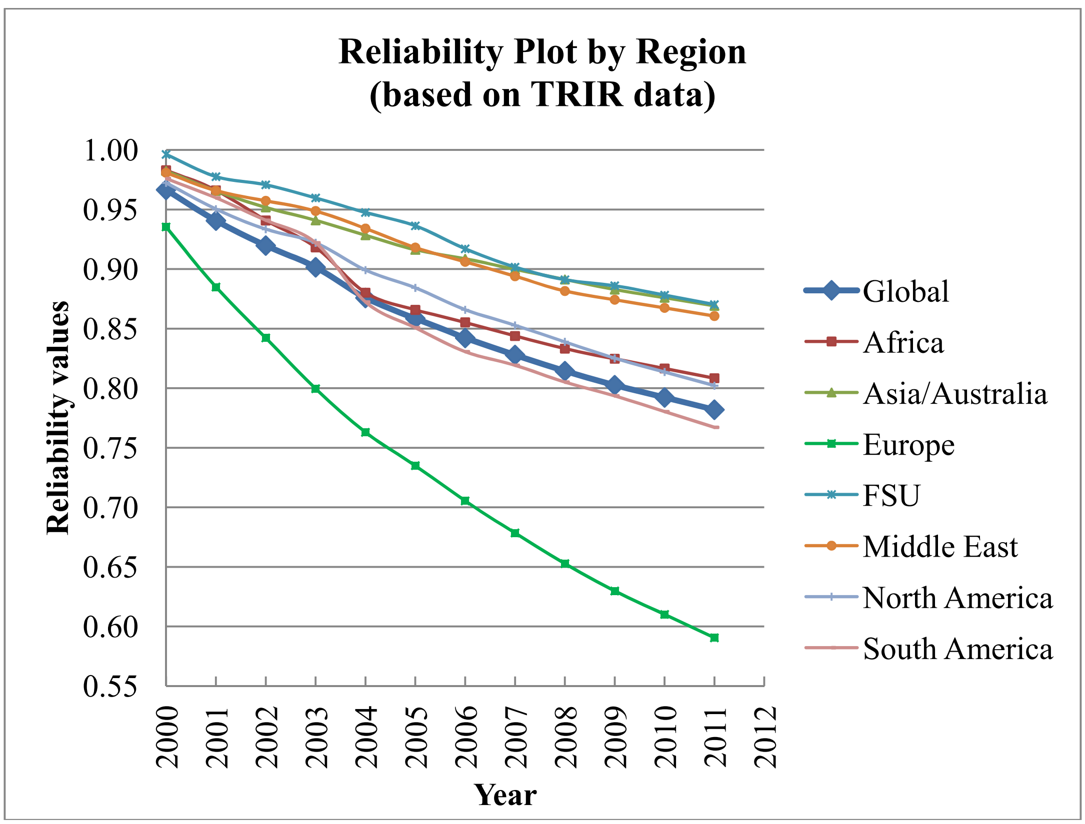


Figure 5-5 Reliability Plot by Region Based on the TRIR Data

5.3 Task 3: Model Calibration

5.3.1 MATLAB Results for the Seven Unknown Reliabilities Used as Direct Input for the Model

A MATLAB code was developed to solve the seven unknowns entered into the model as input reliability values. This code has been included in its entirety in Appendix III. As described in Section 4.2, a system of seven equations and seven unknowns were prepared. The results produced by the MATLAB code are presented in Table 5-8. Once the seven unknowns are estimated it is possible to obtain the reliability of the system under average conditions.

Table 5-8 MATLAB Results by Year for Seven Unknown Reliabilities

Year	Rw	Rcoo	Ri	Rpo	Rsp	Rrr	Rvl
2000	0.9755	0.9780	0.9785	0.9760	0.9745	0.9735	0.9745
2001	0.9535	0.9575	0.9560	0.9530	0.9540	0.9525	0.9510
2002	0.9340	0.9380	0.9370	0.9355	0.9350	0.9340	0.9315
2003	0.9155	0.9200	0.9190	0.9170	0.9165	0.9170	0.9140
2004	0.8890	0.8935	0.8945	0.8905	0.8895	0.8900	0.8870
2005	0.8725	0.8770	0.8780	0.8730	0.8725	0.8740	0.8700
2006	0.8555	0.8620	0.8610	0.8565	0.8555	0.8580	0.8530
2007	0.8410	0.8485	0.8470	0.8425	0.8420	0.8450	0.8380
2008	0.8275	0.8360	0.8355	0.8300	0.8275	0.8325	0.8235
2009	0.8170	0.8255	0.8260	0.8190	0.8160	0.8210	0.8120
2010	0.8070	0.8175	0.8175	0.8080	0.8050	0.8100	0.8010
2011	0.7965	0.8070	0.8070	0.7970	0.7940	0.8010	0.7905

Where:

Rw: is reliability of weather; Rcco: is reliability of coordination; Ri: is reliability of intelligence; Rpo: is reliability of price of oil; Rsp: is reliability of shareholder pressure Rrr: is reliability of royalty regime; Rvl: is reliability of value of life.

Given that the Weibull distribution is widely used in reliability and life data analyses due to its versatility, another MATLAB code was also developed to fit a two parameter Weibull distribution function to each one of the seven reliability outputs (also known as elements of direct input) presented in Table 5-8. This code is presented in Appendix IV of this document.

The Weibull distribution was chosen to fit the data, given that this distribution has hazard rate functions that is not constant over time; thus, providing a necessary alternative to the exponential failure law. The Weibull parameters found for each one of those seven elements are presented in Table 5-9.

Table 5-9 Weibull Parameters for the Seven Reliability Elements of Direct Input

Weibull parameters	Rw	Rcoo	Ri	Rpo	Rsp	Rrr	Rvl
θ	66.14	69.19	70.08	65.57	63.7	70.06	63.43
β	0.846	0.854	0.848	0.854	0.860	0.863	0.850

The Weibull parameters (θ and β) can be described as follows:

The Weibull "shape parameter" Beta (β) is referred also known as the Weibull slope. This is because the value of β is equal to the slope of the line in a probability plot. Weibull distributions with $\beta < 1$ have a failure rate that decreases with time, also known as early-life failures. Weibull distributions with β close to or equal to 1 have a fairly constant failure rate similar in shape to the exponential (Ebeling 1997), indicative of useful life or random failures.

Theta (θ) the "scale parameter", that influences both the mean and the spread, or dispersion, of the distribution indicates that 63.2% of all Weibull failures will occur by time t= θ regardless of the value of the shape parameter (Ebeling 1997).

The shape parameter Beta (β), and the scale parameter Theta (θ), affect Weibull distribution characteristics. Such as, the shape of the provability density function curve f(t), the reliability R(t) and the failure rate λ(t).

Probability density function equation

$$f(t) = -\frac{dR(t)}{dt} = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1} e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$

Reliability equation

$$R(t) = e^{-\left(\frac{t}{\theta}\right)^{\beta}}$$

Failure rate equation

$$\lambda(t) = \frac{\beta}{\theta}\left(\frac{t}{\theta}\right)^{\beta-1}$$

5.3.2 Monte Carlo Simulation for Average Conditions of System Reliability

The Weibull parameters for the seven elements of direct input are now known. Therefore, using these parameters and the equations presented above, it is possible to predict the number of accidents of an offshore platform for a given year under average conditions.

Therefore, to achieve this objective the reliability values of the seven elements of direct input can be calculated for a particular year using the reliability equation of a Weibull distribution and the already calculated parameters (see Table 5-9). These reliability values are substituted in the model (refer to Figure 4-6). Then, the model is run using the commercially available software, @RISK, to obtain a Monte Carlo simulation for the system reliability under average conditions.

Figure 5-7 shows the result of simulation for system's reliability for the year 2011 as presented by @RISK software. The mean reliability value is 0.79 with a maximum of 0.98 and a minimum of 0.6 (see summary statistics for the Reliability of the System in Figure 5-7). Using this approach, the reliability values for the years 2000 to 2011 were estimated and compared to the calculated reliability using OGP data (see Table 5-7 "Global" column). The results that involve minimum maximum and mean values are presented in Table 5-10 - additionally standard deviation, 5 percentile and 95 percentile are also presented. As the table below shows the estimated mean values are very close to the calculated reliability values using the OGP data. The results are illustrated in Figure 5-6.

Table 5-10 Estimated Reliability Values for the Years of 2000 to 2011 Using the Revised Model Approach

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
min	0.7876	0.6930	0.7042	0.6521	0.6848	0.5957	0.6397	0.6254	0.6540	0.6424	0.6012	0.6044
max	1.0000	1.0000	1.0000	0.9729	0.9744	0.9814	1.0110	0.9431	0.9560	0.9962	0.9903	0.9883
mean	0.9060	0.8856	0.8779	0.8668	0.8544	0.8393	0.8290	0.8182	0.8105	0.8022	0.7944	0.7855
Std Dev	0.0492	0.0553	0.0557	0.0539	0.0548	0.0582	0.0575	0.0573	0.0592	0.0626	0.0596	0.0605
5%	0.8128	0.7995	0.7840	0.7700	0.7595	0.7346	0.7363	0.7183	0.7105	0.6944	0.6955	0.6806
95%	0.9825	0.9700	0.9596	0.9486	0.9367	0.9304	0.9147	0.8995	0.9021	0.9021	0.8870	0.8808
OGP	0.9665	0.9406	0.9197	0.9015	0.8758	0.8586	0.8422	0.8279	0.8144	0.8025	0.7922	0.7819

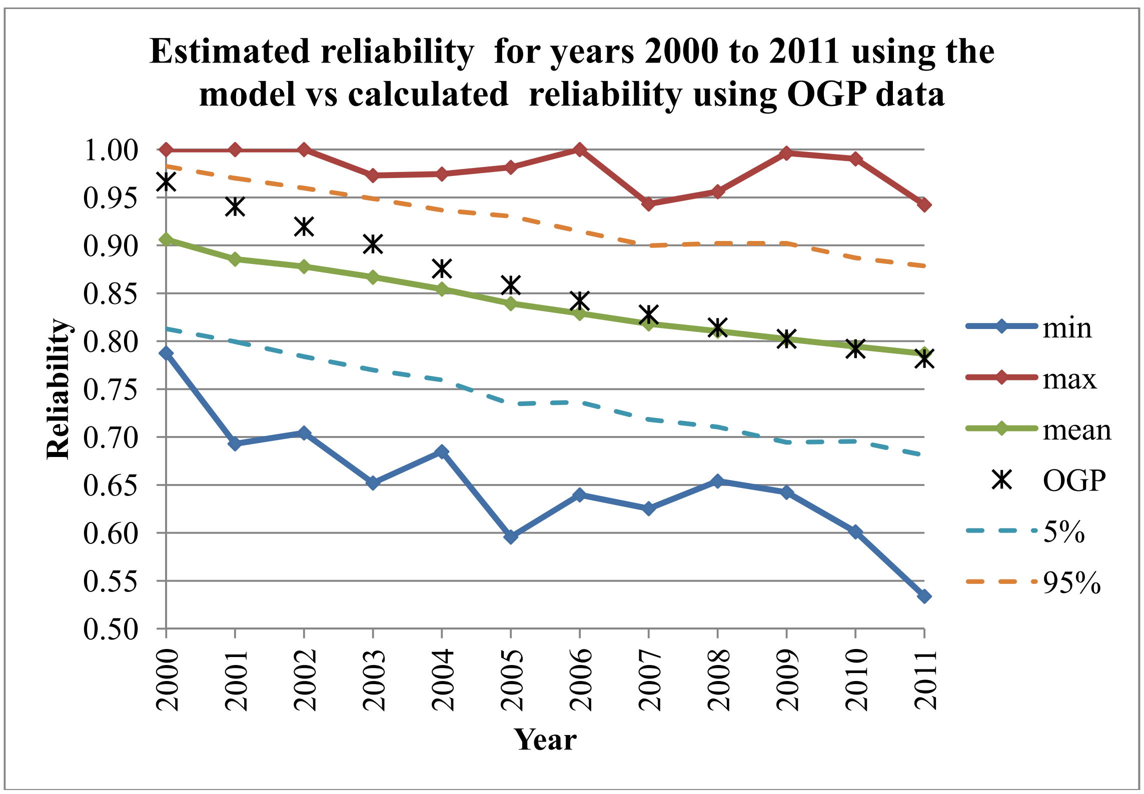


Figure 5-6 Estimated Reliabilities Using Model and Monte Carlo Simulations for the Years 2000 to 2011 Versus Reliability Calculated From OGP Data

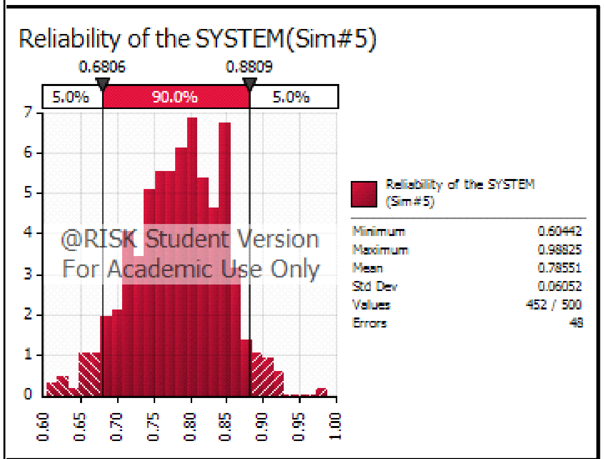
For an occupational safety analysis using this model, lower reliability values such as 5 percentile, represents the maximum number of accidents. Therefore, if necessary to keep a very conservative approach, occupational safety analysis for a particular year can be obtained using this value as worst case scenario. Another interesting outcome of the simulation using @RISK is the visualization of the effect that the inputs have on the output mean (refer to Figure 5-7); for example, "price of oil" has a considerable effect compared with all the others in reducing the System Reliability. On the contrary, the element: "procedures" has an effect in increasing the output mean of System Reliability.

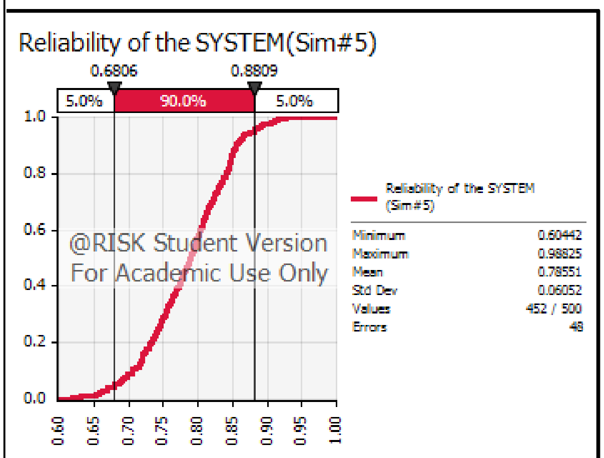
Once the system reliability has been calculated for several years (let's say years 2000 to 2011 as shown in Table 5-10) the reliability outputs can be fitted again in a two parameter Weibull distribution using the MATLAB code developed in Section 5.3.1 (Appendix IV). Once the parameters Theta (θ) and Beta (β) are found for the reliability of the system under the average conditions defined by OGP data, they can be used to predict system reliability or failure rate for any given year. This prediction will not require seven input reliability values given that they have been already used to calculate the Weibull parameters for System reliability under average conditions.

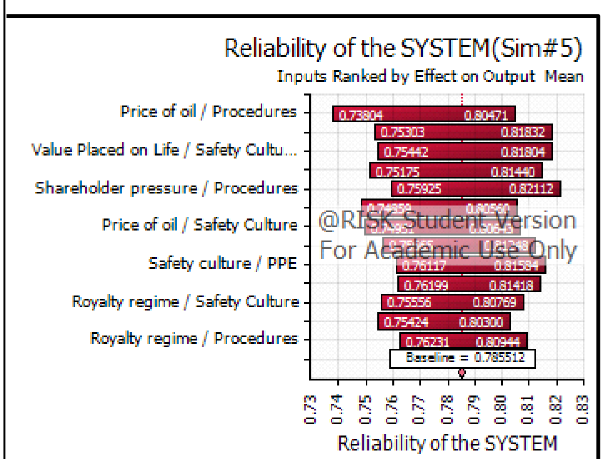
@RISK Output Report for Reliability of the SYSTEM (Sim#5)

Performed By: PARAND

Date: April-16-13 3:42:53 PM







Simulation Summary Information	
Workbook Name	@RISK simulation for Reliab
Number of Simulations	5
Number of Iterations	500
Number of Inputs	58
Number of Outputs	29
Sampling Type	Latin Hypercube
Simulation Start Time	16/04/2013 15:38
Simulation Duration	00:00:03
Random # Generator	Mersenne Twister
Random Seed	1487937672

Summary Statistics for Reliability of the SYSTEM

Statistics		Percentile	
Minimum	0.604424314	**5%**	0.680626564
Maximum	0.98825078	**10%**	0.706457342
Mean	0.785511676	**15%**	0.720796374
Std Dev	0.060520275	**20%**	0.734614509
Variance	0.003662704	**25%**	0.743007628
Skewness	-0.170169235	**30%**	0.753135595
Kurtosis	2.920714731	**35%**	0.762512302
Median	0.789210993	**40%**	0.773126523
Mode	0.845945202	**45%**	0.780271709
Left X	0.680626564	**50%**	0.789210993
Left P	5%	**55%**	0.797299338
Right X	0.880894916	**60%**	0.805108949
Right P	95%	**65%**	0.811818765
Diff X	0.200268352	**70%**	0.820832024
Diff P	90%	**75%**	0.829430834
#Errors	48	**80%**	0.84118815
Filter Min	Off	**85%**	0.847375835
Filter Max	Off	**90%**	0.85560333
#Filtered	0	**95%**	0.880894916

Change in Output Statistic for Reliability of the SYS

Rank	Name	Lower	Upper
1	Price of oil / Proc	0.7380409	0.804709073
2	Shareholder pres	0.7530312	0.818318979
3	Value Placed on	0.7544161	0.818041467
4	Safety culture / S	0.7517536	0.814399942
5	Shareholder pres	0.7592547	0.821121244
6	Value Placed on	0.7485926	0.805595506
7	Price of oil / Safe	0.7495088	0.806434267
8	Value Placed on	0.7566457	0.812480627
9	Safety culture / P	0.7611731	0.815840133
10	Procedures / Saf	0.7619862	0.814175965
11	Royalty regime /	0.7555601	0.807687544
12	Motivation / Scor	0.7542385	0.803000612
13	Royalty regime /	0.7623144	0.809442532
14	Price of oil / Trair	0.7626137	0.807326213

Figure 5-7 Monte Carlo Simulation Results to Obtain System Reliability Using @RISK for the Year 2011

5.4 Task 4: Specific Case Run

5.4.1 Component Reliability Adjustment

To predict accident frequency for a specific scenario as in the case of Newfoundland and Labrador platform, the model is run following adjustment of the base case component reliabilities in line with the safety environment of the installation under study. This adjustment is made based on expert opinion.

Attwood (2006) suggested that the degree of component reliability adjustment is based on the opinion of experts familiar with both base (average global) and specific case safety conditions. The experts assign scores from one to ten for each factor, representing the component's specific case conditions, compared to global average, which is represented by a score of five. Higher scores, in all cases, represent situations more favorable to safety results and vice versa (Attwood 2006).

The transformation of expert's scores to adjust components reliabilities as proposed by Attwood 2006 should be modified for the following reasons:

- Attwood (2006) proposes using a "power 2" function. Therefore, making the changes in component reliability proportional to the square of the ratio of specific case to average case score (average case score equals 5). For example, an assigned score of 6 would produce a component reliability increase of $(6/5)^2$, this value is then multiplied by the correspondent base component reliability to obtain the new component reliability corresponding to the particular case study (Atwood 2006). The problem of using Attwood's approach for this research is that most of Attwood's calculated factors for NL are higher than 1 (See Figure 5-8). Therefore, the multiplication of Attwood's calculated factors by the average base component reliabilities estimated for this research exceed 1 for most of the elements of the model. Results higher than one are erroneous because reliability values are probability values and should range between zero and one.

Factor	Expert score	Transformed Factor	Ratio Squared
External Factor			
Value placed on life	9	Value placed on life	3.24
Price of oil	10	Price of oil	4
Shareholder pressure	3	Shareholder pressure	0.36
Royalty regime	4	Royalty regime	0.64
Corporate Factor			
Safety culture	8	Safety culture	2.56
Safety training	7	Safety training	1.96
Safety procedures	9	Safety procedures	3.24
Direct Factor			
Attitude	6	Attitude	1.44
Motivation	7	Motivation	1.96
Lack of fatigue	8	Lack of fatigue	2.56
Coordination	5	Coordination	1
Fitness	6	Fitness	1.44
Knowledge	8	Knowledge	2.56
Intelligence	5	Intelligence	1
Safety design	7	Safety design	1.96
Weather	1	Weather	0.04
PPE	9	PPE	3.24

Figure 5-8 Expert Score Transformation as per Attwood 2006

- Attwood's base component reliabilities obtained for his doctoral thesis were very low and therefore the multiplication of the base component reliabilities by the calculated factors were considerably increasing the reliability of components for the specific case, but these values did not exceed one. Nonetheless, it is important to note that component reliabilities for average conditions and specific cases should always be high and very close to one (at least for the first years where the model starts calibrating). In this context, small reliability values do not reflect average offshore safety conditions, given that offshore operation demand high occupational safety standards.

In this research, high reliability values were found (see Table 5-7). These values better represent the safety conditions of an average offshore platform, considering that there are few occupational accidents in relation with the number of hours worked.

Therefore, expert score was transformed using a different approach, as it is presented in the equation below:

$$\boxed{\mathrm{Re}\,liability_{(NL)} = (\mathrm{Re}\,liability_{(average\_condition)})^{\left(\frac{10-ExpertScore}{5}\right)}}$$

The power function:

$$\boxed{\frac{10-ExpertScore}{5}}$$

This function transforms expert opinion into a useful power index based on the following criterion:

If expert score is 10 (maximum possible score for the reliability component and higher than global average). Therefore, the power function will be:

$$\frac{10-10}{5}=0$$

Then: $R^0=1$ (maximum reliability value)

If expert score is 5 (meaning that conditions of the particular platform are same as global average). Then the power function will be:

$$\frac{10-5}{5}=1$$

Then: $R^1=R$ (same reliability value as average condition)

If expert score is lower than 5 (meaning that the reliability of that element for the particular platform is lower than the global average)

$$\frac{10-1}{5}=1.8$$

Then: $R^{1.8}=lowerR$ (lower reliability value than global average)

The following table shows the calculated exponents for the Newfoundland and Labrador offshore platforms based on expert opinion using the approach presented above.

Table 5-11 Expert Score Transformation for Newfoundland and Labrador Platforms

Factor	NFLD	Factor	Exponent
Value placed on life	9	Value placed on life	0.2
Price of oil	10	Price of oil	0
Shareholder pressure	3	Shareholder pressure	1.4
Royalty regime	4	Royalty regime	1.2
Safety culture	8	Safety culture	0.40
Safety training	7	Safety training	0.60
Safety procedures	9	Safety procedures	0.20
Attitude	6	Attitude	0.8
Motivation	7	Motivation	0.6
Lack of fatigue	8	Lack of fatigue	0.4
Coordination	5	Coordination	1
Fitness	6	Fitness	0.8
Knowledge	8	Knowledge	0.4
Intelligence	5	Intelligence	1
Safety design	7	Safety design	0.6
Weather	1	Weather	1.8
PPE	9	PPE	0.2

5.4.2 Reliability of the Specific Case versus the Reliability of the Global Average Conditions

It is important to note that the experts rated the Newfoundland and Labrador offshore operation as of higher safety performance than the average global conditions (at least for 12 of the 17 elements assessed on Table 5-11). The reliability results of the overall system calculated with the approach presented in Section 5.4.1 are presented in Table 5-12. The results agree with the experts' opinion. Overall yearly reliability of the system of NL offshore operations are higher than the global average, which conversely indicates that the TRIR in NL is lower than the TRIR global average

Once the reliability of the elements of the system for the NL platform has been determined, they are substituted in the model and then run for the particular case under study. Figure 5-9 shows the system reliability results of the Monte Carlo simulation run for NL platform for the year 2011. Similarly to what is shown in Figure 5-9, Monte Carlo simulations are run to calculate reliability values for each year under study (2000 to 2011). Table 5-12 shows a summary of the calculated mean reliabilities for the global average conditions and the NL platform safety conditions.

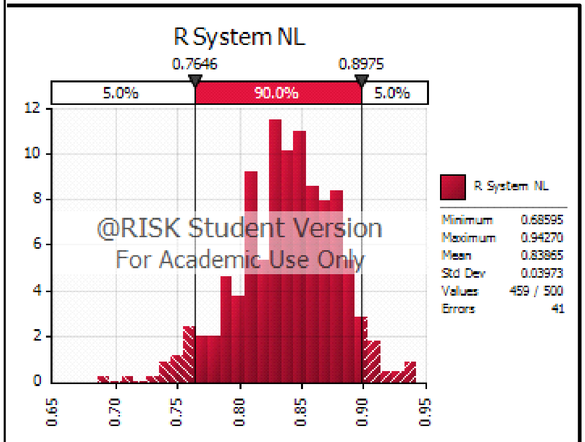
Table 5-12 Calculated Reliabilities (Mean Value) for Average Conditions and NL

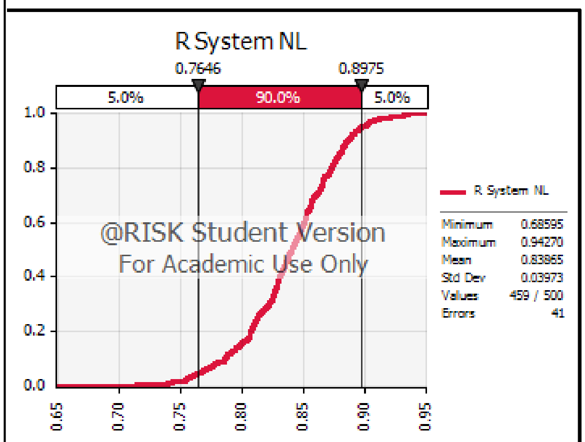
Year	Average conditions system reliability	NL system reliability
2000	0.9758	0.9827
2001	0.953 5	0.9662
2002	0.9345	0.9519
2003	0.9165	0.9384
2004	0.8898	0.9182
2005	0.8730	0.9055
2006	0.8562	0.8926
2007	0.8420	0.8817
2008	0.8283	0.8712
2009	0.8172	0.8627
2010	0.8066	0.8546
2011	0.7960	0.8465

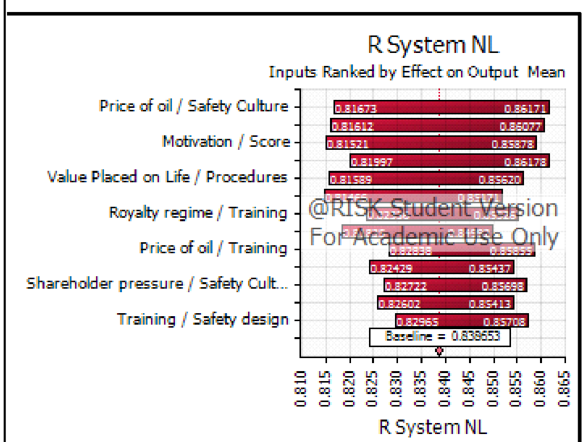
@RISK Output Report for R System NL

Performed By: PARAND

Date: May-10-13 8:19:24 PM







Simulation Summary Information	
Workbook Name	@RISK simulation for Reli
Number of Simulations	1
Number of Iterations	500
Number of Inputs	58
Number of Outputs	30
Sampling Type	Latin Hypercube
Simulation Start Time	10/05/2013 20:18
Simulation Duration	00:00:02
Random # Generator	Mersenne Twister
Random Seed	623937671

Summary Statistics for R System NL

Statistics		Percentile	
Minimum	0.685951776	5%	0.7646384
Maximum	0.942699907	10%	0.7861208
Mean	0.838653081	15%	0.7977069
Std Dev	0.039726316	20%	0.8078105
Variance	0.00157818	25%	0.8126446
Skewness	-0.364144507	30%	0.8220942
Kurtosis	3.308940091	35%	0.8276014
Median	0.840611271	40%	0.8308282
Mode	0.806948538	45%	0.8354278
Left X	0.764638394	50%	0.8406113
Left P	5%	55%	0.8459519
Right X	0.897537935	60%	0.8510668
Right P	95%	65%	0.8550511
Diff X	0.132899541	70%	0.8599902
Diff P	90%	75%	0.866287
#Errors	41	80%	0.8732947
Filter Min	Off	85%	0.8800286
Filter Max	Off	90%	0.8860159
#Filtered	0	95%	0.8975379

Change in Output Statistic for R System NL

Rank	Name	Lower	Upper
1	Price of oil / Safet	0.8167327	0.8617053
2	Value Placed on	0.8161173	0.8607721
3	Motivation / Scor	0.8152105	0.8587799
4	Weather / Score	0.8199724	0.8617761
5	Value Placed on	0.8158856	0.8561977
6	Attitude / Score	0.8146627	0.8517117
7	Royalty regime /	0.8233591	0.8552587
8	Safety culture / S	0.8183489	0.8499201
9	Price of oil / Trair	0.8283792	0.8585463
10	Shareholder pres	0.8242881	0.8543711
11	Shareholder pres	0.8272186	0.8569766
12	Procedures / Safe	0.8260219	0.8541295
13	Training / Safety	0.8296528	0.8570815
14	Procedures / Kno	0.8263379	0.853114

Figure 5-9 Monte Carlo Simulation for NL System Reliability Year 2011

5.4.3 Model Validation

To assess the effectiveness of the model, the estimated reliability values presented in Table 5-12 were transformed into predictions of the number of accidents per year (TRIR) and then compared with the TRIR data (OGP data for global average and CNLOPB data for NL). The results of the comparison are presented in Table 5-13.

Table 5-13 Estimated TRIR for Global and NL Operations versus Obtained Data

	OGP (TRIR)				CNLOPB (TRIR)			
Year	**original data**	**transformed data (100 workers)**	**estimated with model (100 workers)**	**%Error**	**original data**	**transformed data (100 workers)**	**estimated with model (100 workers)**	**%Error**
2000	7.64	3.35	2.42	-27.84	10.16	4.45	1.77	-60.23
2001	5.90	2.59	2.18	-15.71	9.49	4.16	1.61	-61.36
2002	4.78	2.09	2.06	-1.59	8.04	3.52	1.52	-56.91
2003	4.15	1.82	1.97	8.33	11.45	5.02	1.46	-70.93
2004	5.87	2.57	1.91	-25.76	4.36	1.91	1.41	-26.02
2005	3.93	1.72	1.86	8.00	6.01	2.63	1.38	-47.68
2006	3.73	1.64	1.82	10.73	6.59	2.89	1.35	-53.30
2007	3.26	1.43	1.78	24.52	6.57	2.88	1.32	-54.03
2008	3.09	1.35	1.75	29.64	8.51	3.73	1.30	-65.09
2009	2.70	1.18	1.72	46.04	8.09	3.55	1.28	-63.82
2010	2.35	1.03	1.70	64.97	4.31	1.89	1.27	-32.98
2011	2.83	1.24	1.68	35.29	5.29	2.32	1.25	-46.06

It is important to note that the original CNLOPB data is transformed similarly as the original OGP data (refer to Section 5.2.2). This transformation is based on the assumption that 100 people are operating in an offshore platform and 50% of them are working continuously all year round.

The results presented in Table 5-13 are summarized and illustrated in Figure 5-10. The figure shows that the number of recorded injuries decreases with time in all cases. The most significant difference between estimated values and real data is that the estimated values tend to present smoother trend lines than the actual real data. The reason is that the real data includes certain degree of randomness, but the estimated values are based on a general trend.

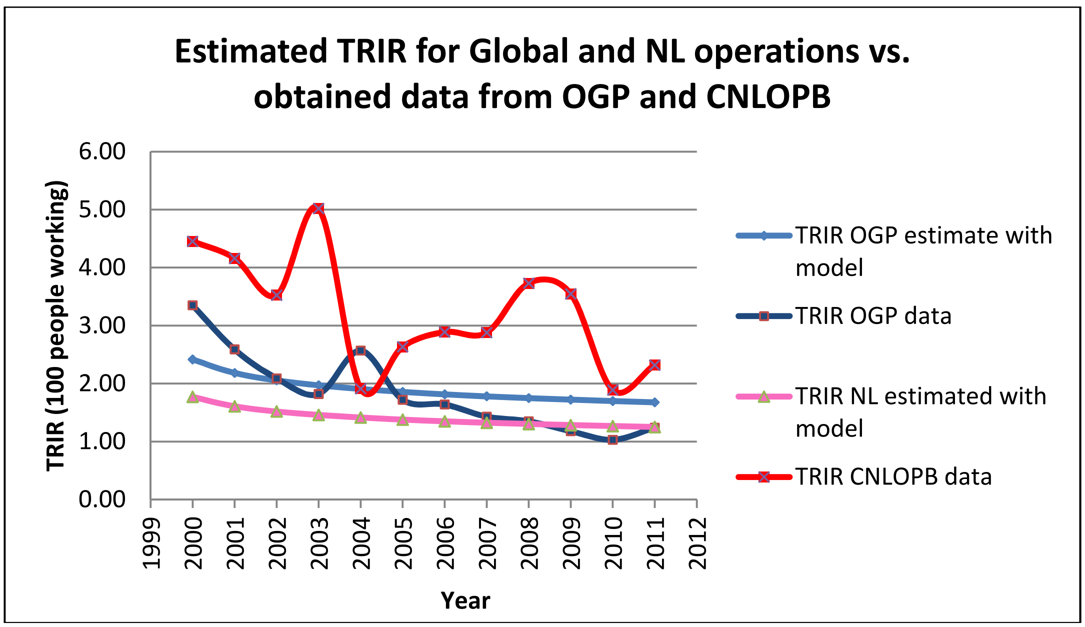


Figure 5-10 Estimated TRIR for Global and NL Operations versus Obtained Data

Larger discrepancies between the estimated TRIR and the data of TRIR are found in the first years of study (i.e. 2000, 2001) for the global average and NL cases. These results can be explained as follows:

The TRIR data values are relatively small and are showing a decreasing trend by year. For example, looking at the OGP data, TRIR values in 2000 and 2011 were 7.64 and 2.83, respectively. When the data are transformed for 100 people working in a platform, the TRIR values become 3.35 and 1.24, respectively, for 2000 and 2011 (Table 5-13). It should be noted that since the TRIR values are small a small changes results in a large error. Nonetheless, the magnitude of the errors also decrease and this is an iterative process that improves with time as more data become available. As such, the large errors presented on Table 5-13 do not necessarily indicate poor results on the estimation of TRIR values. Therefore, we can consider that the estimation for global average conditions is reasonably close to the data.

The NL statistics (i.e. TRIR data) is more sensitive than the global average. Therefore, the NL data is more spread than the global average. The reason is that the data is based in a few numbers of platforms; so changes in one will affect considerably the overall statistics (Refer to Figure 5-10).

When comparing errors found for global average conditions and NL platforms it has been observed that larger errors are related to NL case. The main reason is that the collected data do not reflect the experts' opinion (experts' opinion is a key element for model calibration). The experts' opinion, rated the Newfoundland offshore safety environment equal or superior to the average global situation in more than 86%

(Attwood 2006, pp., 225). However, the data shows that global average has a better safety performance with lower TRIR (refer to Table 5-13 and Figure 5-10).

Although, similar performance indicators are being compared (TRIR for OGP and RIFR for NL), unexpected results are seen. As explained above the Newfoundland safety performance is significantly worse than global average in most of the years, with exception of the year 2004. Similar results were found by Attwood (2006) for the period of his research (2000-2004).

Attwood (2006) provided some possible explanations to justify these results. First, Attwood suggested that the RIFR database was possibly contaminated by inclusion of data from workgroups other than offshore platforms. This supposition was confirmed in this research (Figure 5-11) where air transport, sea transport and diving have been included in the CNLOPB injury statistics. On the contrary, the global average statistics does not consider accidents outside offshore installations (Figure 2-1).

The second explanation has to do with the over reporting of occupational accidents due to formed worker unions. It is possible to see that the differences are persisting and that in general the trends have not changed from year 2005 to 2011.

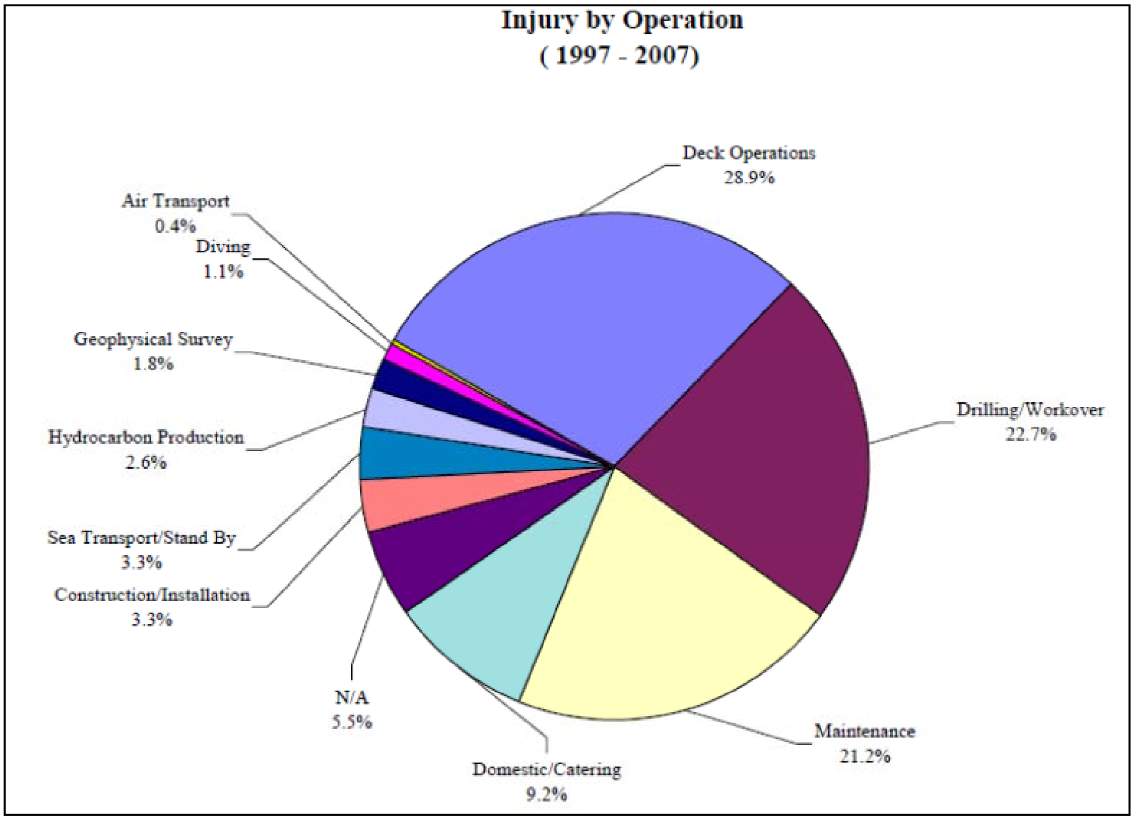


Figure 5-11 CNLOPB Injuries Report Pie Chart

It can also be argued that the sources of error may directly be associated with the model, particularly "expert opinion" gathered data. Where large errors mean that the data do not reflect real safety conditions of the specific case study. To assess these options it is recommended first to discard the two explanations presented above. Then, safety data for NL should be extracted from OGP reports instead from CNLOPB reports. In order to perform this task an extensive data processing of OGP reports is required. Such level data interrogation was beyond the scope of this project and the main objective sought was to transform the model from a deterministic framework to a probabilistic one with a further development of the risk assessment tool.

Usually main safety statistics are reported in OGP documents by regions; such as North America (which includes USA and Canada). In the data often offshore and onshore statistics are mixed and presented as a single safety indicator. Therefore they cannot be used directly to extract offshore safety parameters for a specific region such as NL. However, the OGP documents have an appendix section, in which each reported accident or incident has been briefly described, although operators name and sometimes specific location details is kept anonymous. Detailed analysis of the appendices may give the estimated NL safety indicators required for the comparison and model calibration and therefore, clarify the real source of the problem.

The discrepancies between the data and the results predicted by the model for the NL offshore platform make difficult the task of model validation. In order to have an accurate model validation, it is necessary to ensure that the data collected for the case study followed the same format and procedures as the global average data. These statistics mainly depend on the safety requirements of the region, country or the operator where offshore the facility is operating.

This research is the first step forward towards development of a probabilistic model. It is acknowledged that, model validation is required to prove the operability of the model. This research has served to clearly identify specific problems obstructing model validation and therefore clear recommendations are implemented for future work. Application of the Proposed Reliability Model for Predicting Safety Performance

5.4.4 Application of the Proposed Reliability Model for Predicting Safety Performance

The model can be further used to estimate future TRIR indices or other safety performance indicators. In order to do this, the reliability values should be used to calculate a two-parameter Weibull distribution (θ and β) that fits system reliability outputs (as described in Section 5.3.1). The MATLAB code (see appendix IV) developed for Task 3 should be used again to re-calculate θ and β parameters. Once the parameters are calculated, the reliability values can be obtained for any time in the future and therefore the failure probabilities and then TRIR or any other desired safety performance indicator. This approach can be used for elements of the model or overall system reliability. The advantage of using this tool is the possibility to predict safety conditions at any specific point in time. Further, it can be used to identify elements of the system that require improvement to reduce overall incidents. For example, Table 5-14 presents the estimated Weibull parameters for global average conditions and NL specific case.

Table 5-14 Estimated Weibull Parameters for Average Conditions and NL Platform

	Average Conditions Parameters	NL Parameters
θ	65.21	91.36
β	0.853	0.86

Task 5: Risk Calculation

Risk is essentially a combination of the likelihood that an event will occur, along with the severity of consequences if it does occur. By combining severity and likelihood, an organization can have the most complete picture possible and can rationally make assessments about which risks should be given the priority. While risk analysis cannot predict the future with certainty, it can help to select the best strategies based on the available information.

Previous sections of this document have been developed in order to calculate the likelihood of an occupational accident happening in an offshore platform. Monte Carlo simulations where performed to obtain number of occupational accidents as a probabilistic outcome (in terms of TRIR) in a unit year. The following sections describe how severity is classified for the risk calulcations.

5.4.5 Classification of Severity of Occupational Accidents

The severity of occupational accidents in offshore platforms can be classified using the classification system proposed by the Health and Safety Report prepared by Det Norske Veritas Industry AS, for the Health and Safety Organization of United Kingdom (Det Norske Veritas Industry 2003) . This classification is presented below in Table 5-15.

Table 5-15 Severity of Occupational Accidents in Offshore Platforms (Det Norske Veritas Industry 2003)

Occurrence	Severity Level Description
Fatality	Considered as a Catastrophic outcome
Major Injury	Considered as a Significant outcome
Over Three day Injury	Considered as a Moderate outcome
Dangerous Occurrence	Considered as a low risk outcome

The following is a summary of the definition of some of the terms presented in Table 5-15 that require a more precise description. The description is based on the Reporting of Injuries Disease and Dangerous Occurrences Regulation (RIDDOR) 1995:

Major Injury includes the following (UK 1995; UK. 1995):

- Any fracture other than finger, thumb or toes.
- Any dislocation of shoulder, hip, knee or spine.
- Any amputation.
- Loss of the sight of an eye (whether temporary or permanent).
- Chemical or hot metal burn to the eye or any penetrating injury to the eye.
- Any injury which results in electric shock and electric burns leading to unconsciousness and requires resuscitation or admittance to hospital for 24 hours or more.
- Any other injury leading to hypothermia, heat induced illness or unconsciousness requiring resuscitation or admittance to hospital for 24 hours or more.
- Loss of consciousness caused by asphyxia or lack of oxygen or exposure to a biological agent or harmful substance.
- Absorption of any substance by inhalation, skin or ingestion causing loss of consciousness or acute illness requiring medical treatment.
- Acute illness requiring medical treatment where there is reason to believe the exposure was to biological agents, its toxins or infected materials.

Dangerous Occurrences includes the following (UK. 1995):

- Collapse of, the overturning of, or the failure of any load bearing part of any lifting machinery (includes lifts, hoists, cradles, access platforms, excavators, pile driving frames and fork lift trucks).
- Pressure systems -The failure of any closed vessel (including a boiler or boiler tube) or associated pipe work.
- Freight containers - The failure of any freight container in any of its load-bearing parts while it is being raised, lowered or suspended.
- Overhead power lines - where plant or equipment comes into contact with insulated lines with voltage exceeding 200 volts, or causes an electrical discharge by coming into close proximity with the overhead line.
- Electrical short circuits or overloads attended by fire or explosion which causes stoppage of plant involved for more than 24 hours, or has the potential to cause the death of a person.
- Explosives causing injury to a person, projection of material beyond the boundary of the site, misfires, failure of shots, unintentional discharges or ignition of explosives.
- Explosions or fires caused by explosion.
- Escape of substances.
- Escape of flammable substances.
- Escape of biological agents.

- Collapse of scaffolding, building or structure.
- Carriage of dangerous substances by road.
- Incidents involving wells, pipelines or pipeline works.

Once the Severity of an activity has been identified, then this can be factored by the likelihood in order to obtain the risk estimation. The analysis can qualitative or quantitative.

The TRIR safety indicator has been used in earlier sections of this research for three reasons: first, it is a very common safety performance indicator; second, is data frequently available for the public and third; because mostly (but not entirely) accounts for events considered of high frequency and low severity. Strictly speaking the TRIR safety indicator describes the number of recordable injuries which includes: fatalities + lost work day cases + restricted work day cases + medical treatment cases; per 1,000000 hours worked. However, fatalities accounts for a very small portion of the TRIR overall numerical value and can be disregarded.

Therefore, given that the TRIR encloses all severity categories presented in Table 5-15 it and cannot be used as the likelihood of a particular severity classification. More detailed and segmented statistical data is necessary to get appropriate quantitative risk estimation (i.e data from fatally, major injury, over three day injury or dangerous occurrence). The following section will present the steps to follow in order to perform a quantitative risk assessment.

5.4.6 Quantitative Occupational Risk Assessment for Offshore Operations

The quantification of occupational risk is usually calculated and presented in terms of Individual Risk Per Annum (IRPA). One needs to select the safety indicator of its interest to obtain the related IRPA. As explained above, TRIR it is a broader safety indicator that encompasses all severity categories. Therefore, it is not considered as an option for the risk assessment developed in this section. If statistical data were available for the four severity categories then the IRPA for each category can be numerically calculated. Ideally data describing major injury, over three day injury or dangerous occurrence will be a perfect fit for the representation of low severity high frequency accidents. Unfortunately, data that describes major injury, over three day injury or dangerous occurrence is not readily available for the public.

From the four Severity Categories presented above, fatality can be described with the Fatal Accident Rate (FAR) statistics of an offshore platform. This safety indicator is frequently available for the public in offshore databases (such as OGP database or CNLOPB data base) and will serve as a perfect example in order to layout the methodology for the risk assessment analysis.

In order to assess IRPA for fatalities, FAR data needs to be converted to IRPA values using actual work pattern data. It is important to mention that offshore personnel may be exposed to risk whilst off shift and in the time of their rotation. However, for this particular research it is assumed that the exposure time is just during working hours (normally 12 hours a day).

The Individual Risk Per Annum (IRPA) for fatalities is then calculated by the following equation:

$$IRPA = FAR_{(2000-2011)} \times \frac{Working\_hour\_person/year}{10^8}$$

Where, the representative FAR for the years 2000 to 2011 can be estimated using the Probabilistic Reliability Model and the Monte Carlo Simulations. The method is similar to that developed in this research for estimating TRIR.

Table 5-16 presents the FAR data exclusively for offshore activities. It should be noted that the OGP Safety Indicators reports (from 2000 to 2011) do not directly provide the FAR data for offshore and therefore, additional processing is required to extract data for offshore activities. This was done using the total number of work hours for offshore activities, and the numbers of fatalities corresponding to offshore activities. OGP data was selected instead of CNLOPB data for this analysis since the third parties and air transport fatalities can be excluded from the analysis.

Table 5-16 Offshore FAR Excluding Third Parties and Air Transport Fatalities (Using the Oil and Gas Producers Database)

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Calculated Offshore FAR	3.77	4.25	2.43	3.02	3.39	1.99	1.44	2.62	1.45	1.77	2.01	1.20

A distribution function was then fitted to the FAR values using the @RISK software in order to develop a probabilistic framework. The results are presented on Figure 5-12. An exponential distribution was selected as the best fit. This distribution was used for the calculation of the IRPA occupational risk assessment indicator.

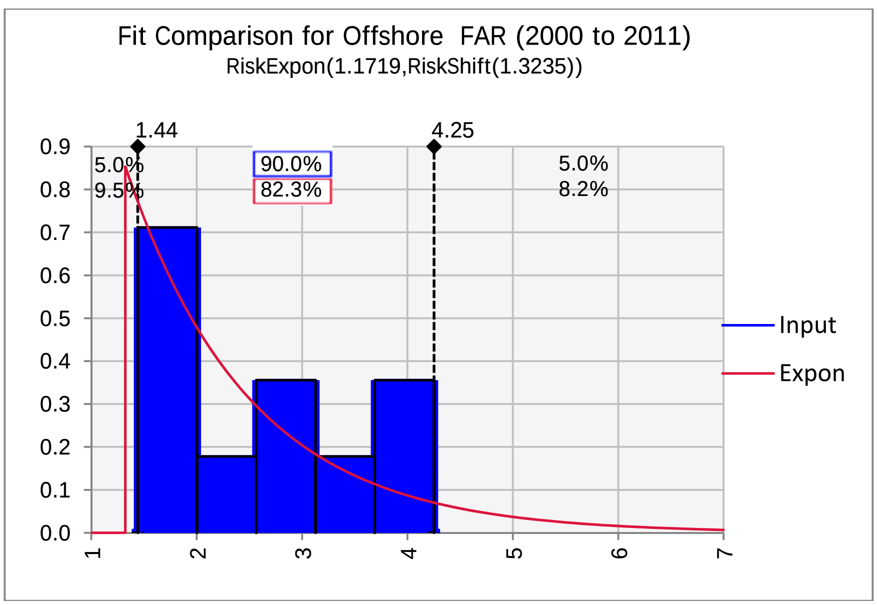


Figure 5-12 Fitting Distribution to Estimate Offshore Fatality Accident Rate (FAR) Values (from 2000 to 2011)

The other variable "working hours person/year" can be defined with a normal distribution. The OGP report of 2011 defines the actual "hours worked" for offshore workers as the number of hours calculated on a 12 hours' workday. Consequently the average hours worked per year varies from 1600 to 2300 hours/person (averaging 2000) depending upon the shift on/off ratio. This value can be transformed into a normal distribution with a mean 2000 hours/person and a standard deviation of 350 hours/person (Figure 5-13). The normal distribution was selected to best describe this parameter for two reasons: i) most of the data are near the middle datum or average of the sample and ii) very few data is near the upper or lower extremes.

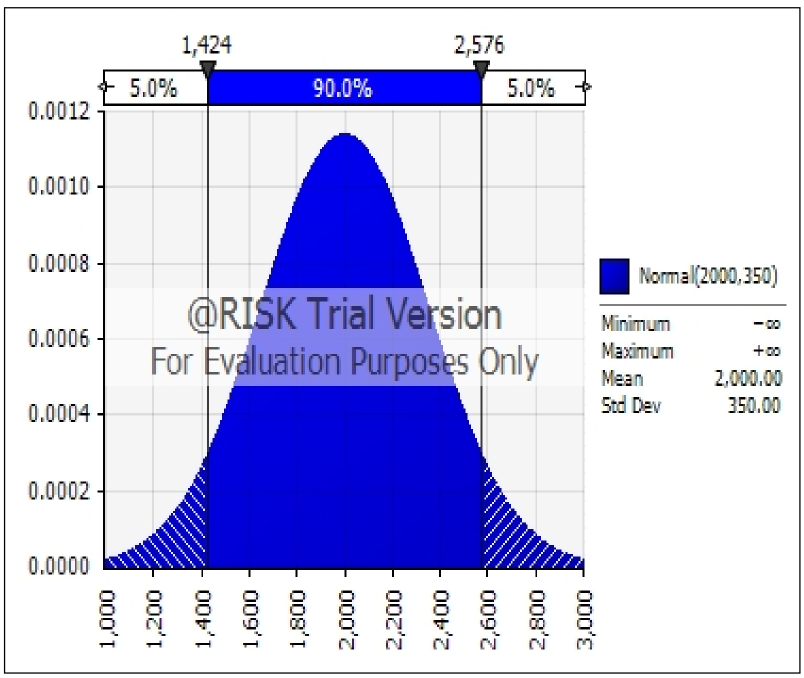


Figure 5-13 Working Hours per Year as Normal Distribution

A Monte Carlo simulation was run to obtain the corresponding IRPA. As shown in Figure 5-14 IRPA mean value is about $5x10^{-5}$ and the 95 percentile of IRPA is approximately $1x10^{-4}$. It is extremely valuable to get the results as a distribution of possible outcomes, since it allows evaluation of extreme probabilities (such as the ones corresponding to the distribution tale) which is one of the major objectives of performing quantitative risk analysis when assessing worst case scenario conditions.

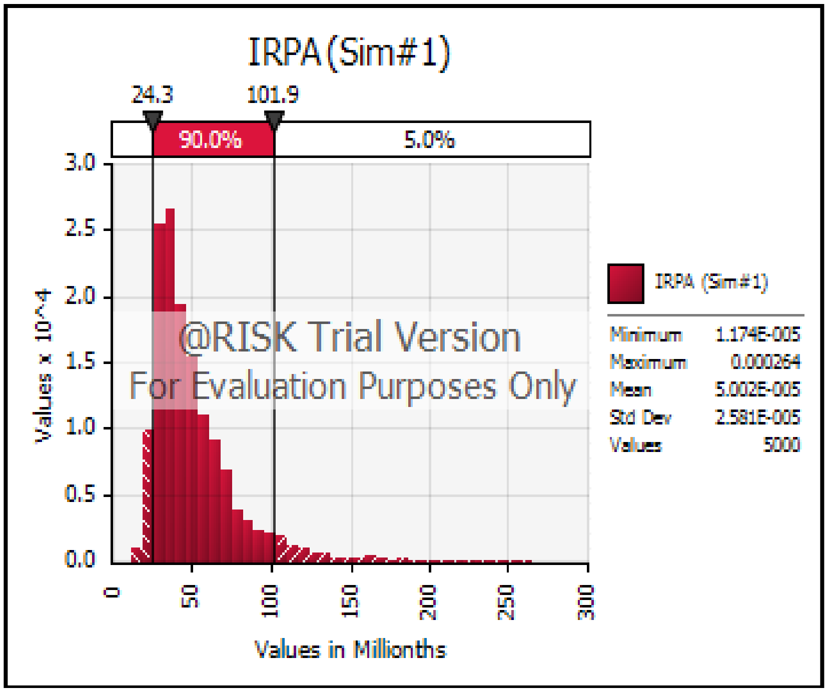


Figure 5-14 Monte Carlo Simulation for the Estimation of IRPA

The estimated risk values (IRPA results obtained as a Monte Carlo Simulations) are then compared to the acceptance criteria. One example largely used in offshore operations is the "ALARP Triangle" (As Low as Reasonably Practicable), refer to Figure 5-15. ALARP is a term used by some companies and regulators to provide a framework for deciding on the level of investment needed for safety programs.

In the lower region of the ALARP triangle the risk is considered negligible, provided that normal precautions are maintained. In this case, the organization or company may spend resources more effectively elsewhere to improve safety, rather than trying to reduce these risks any further.

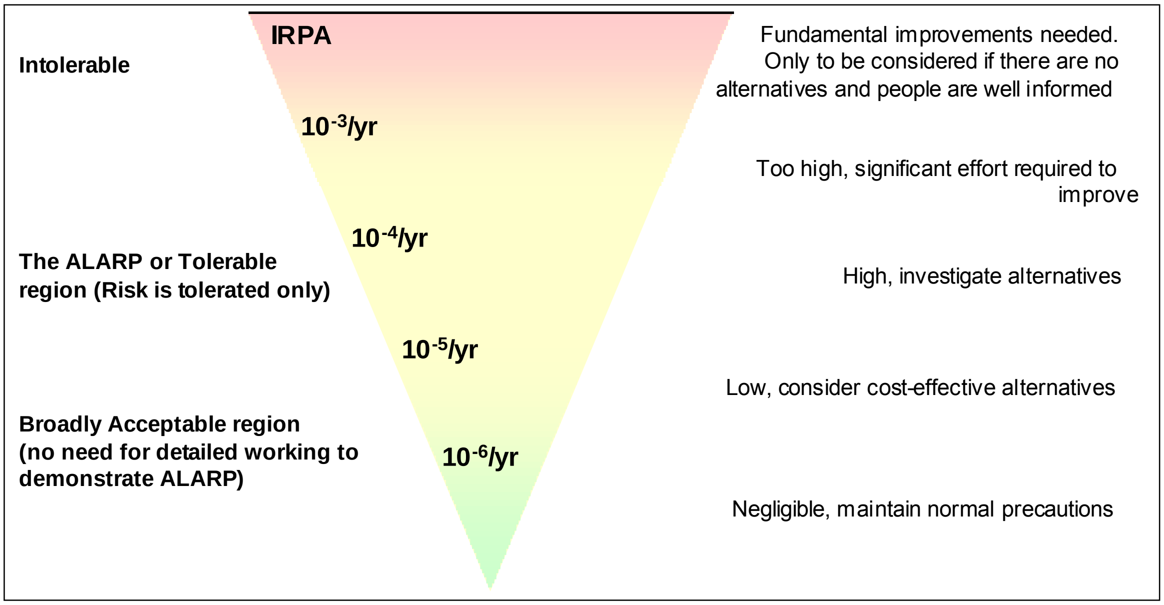


Figure 5-15 ALARP Triangle (From an anonymous company, HSE Manual)

The upper region of the ALARP triangle represents an intolerable risk level, where risk must be reduced. The area in between is the so-called “ALARP Region”. Within this region, decisions on the risk tolerability will have to be based on a balance between business and safety objectives, which will depend on the degree of difficulty to make further improvements. This forms the basis for the “ALARP Principle” whereby any risk that lies between intolerable and negligible levels must be reduced so far as reasonably practicable, or to a level which is “As Low As Reasonably Practicable” (ALARP).

For example, the HSE Manual of an anonymous company has the following guidelines for analysis of risk tolerability regarding worker fatalities:

"*While it is clearly not possible to set single quantitative guidelines on risk acceptability, some broad indicators of the current position can be noted. If the average expectation of life is 70-75 years, then the imposition of a continuing annual risk of death to the individual of 0.01 (one in one hundred years) seems unacceptable. At 0.001 (one in one thousand years), it may not be totally unacceptable if the individual knows of the situation, enjoys come commensurate benefit, and everything reasonable has been done to reduce the risk. Broadly, a risk of death of 1 in 1000 per annum is about the most that is ordinarily accepted under modern conditions for workers and it seems reasonable to adopt it as the dividing line between what is just tolerable and what is intolerable*."

Nonetheless, within this company, an average risk of fatality derived for onshore workers historical statistics is approximately 2.3 fatalities per 10,000 man-years (2.3×10^{-4} fatalities per annum). As a result, work related individual risk in the range of 1 fatality in 1000 man-years to 1 fatality in 10,000 man years is still considered too high under the company's safety standards (Refer to Figure 5-15, ALARP triangle). Examples of the average onshore worker risks in comparison to the "ordinary risks of life" are presented in Table 5-17.

Table 5-17 Examples of Risk Fatality/Year (Anonymous Company)

Risk of Fatality/year		Cause of Risk
1 in 1000	1×10^{-3}	Risk of death in high risk groups within relatively "risky" industries, e.g. mining
2.3 in 10,000	2.3×10^{-4}	Average risk of death for onshore staff
1 in 10,000	1×10^{-4}	General risk of death in traffic accident (UK)
1 in 100,000	1×10^{-5}	Risk of death in an accident at work in the very safest parts of industry
1 in 1 million	1×10^{-6}	General risk of death in a fire or explosion from gas at home
1 in 10 million	1×10^{-7}	Risk of death by being struck by lightning

The mean value of the IRPA results is 5×10^{-5} and the 95 percentile 1×10^{-4} (Figure 5-14). These results are compared against the ALARP triangle on Figure 5-15. The 95 percentile result (worst case scenario) lies in the ALARP or "tolerable region", which means that alternatives should be investigated and risk tolerability will have to be based between balance of business and safety objectives. However, the IRPA mean value lies in the "broadly acceptable" region, so no further analysis is required.

This analysis shows that global average offshore fatalities lie within ALARP region. The above analysis demonstrates the application of the proposed approach. Similar analyses can be performed for the other three severity classifications (Major injury, over three day injury and dangerous occurrence). However, other ALARP triangles have to be specifically created to assess risk levels of each classification taking into account regulations and organizational safety standards. Also, specific data within each category has to be gathered to achieve this objective. Those risk analyses then can be used to improve safety conditions of offshore operations and allocate deployment of resources using the model in order to improve the overall safety.

Calculated risk levels are usually compared with the acceptance criteria set by the organization and/or policies and regulations governing the region under study. Options of risk reducing measures should always be addressed. The process may include a re-evaluation of the risks and of risk reduction measures based on cost-benefit analysis (part of ALARP evaluation).

6 CONCLUSIONS AND RECOMENDATIONS

The Attwood's reliability model (Attwood 2006) for the quantification of occupational accidents in the oil and gas industry has been revised in its entirety from a deterministic framework to a probabilistic approach. As a result a completely new model approach has been developed and proposed for occupational accident hind cast and forecast analyses. Important changes have been made in the numerical approach for the model calibration and model application sections. In addition, Attwood's model was extended a step forward to be used as an occupational risk estimation tool. The modifications have helped to overcome fundamental assumptions and improve accident rate prediction and also increase the model capability. These modifications are summarized as follows:

- Development of a probabilistic approach: The model variables have been transformed and introduced as probabilistic values (functions describing variable characteristics) with the objective of more realistically representing the uncertainties associated with each model element and overall outcome.
- Modifications in model calibration: Important modifications and corrections to the Attwood's approach have been implemented for model calibration. The model has been calibrated using global data as system of seven equations with seven unknowns. A large volume of data from OGP reports (from 2000 to 2012) were extracted and analyzed for this task. The regional OGP data (from seven regions

worldwide) were used to solve the proposed new equations using a code developed in the commercially available software, MATLAB.

- Development of Monte Carlo simulations to get probabilistic outcomes of the model: This approach was an entirely a new contribution to the model. Monte Carlo simulations are widely used in risk analysis, given that there is significant uncertainty in the input variables.
- Modification in expert survey analysis: Important modifications have been implemented to this portion of the research in order to fit the changes applied to the model.
- Testing and validations.
- Risk estimation: This is an entire new step implemented to the model for the occupational risk assessment of offshore operations.

The use of a probabilistic approach in the estimation of occupational accidents is a considerable upgrade to the original model (deterministic approach). Single-point risk assessment methods, place the risk assessor, regulatory agencies and the public in a very difficult position, given the uncertainty associated to the estimation of risk. The risk estimated using the deterministic approach may have span of uncertainty of several orders of magnitude. This can be particularly critical in cases where the single risk estimate is close to the maximum acceptable level. To this end, Monte Carlo simulation has proven to be a very useful tool in risk analysis, furnishing the decision-maker with a range of possible outcomes and their respective probabilities of occurrence. Though the numerical simulation process is inherently complex, tools such as @RISK can assist for the simulations. The results from Monte Carlo simulation cover a wide range of possible outcomes and their likelihood in simple graphs and tables that can be easily understood.

The literature shows that various quantitative models have been developed to address accidents of high severity though low-frequency (such as transport accidents, explosions, etc.) in the offshore oil and gas industry; given that this accidents have a strong impact in the public opinion. Nonetheless, there is still a lack of quantitative models for low severity high frequency accidents, which in time can impose similar danger and represent a large percentage of the annual occupational accidents in the offshore oil and gas sector. The utilization of quantitative models for such accidents considerably improves accident's analysis. Therefore more effective measures can be implemented in strategic way to further reduce the number of occupational accidents in the offshore oil and gas operations.

Like any other occupational accident model, the proposed Occupational Risk Assessment Model relies on expert opinion. This introduces certain advantage and also limitations to the model. The advantage is that expert opinion helps to update and revise constantly the model and therefore helping to adapt to the ever-changing environment and working conditions of offshore installations. On the other hand, the disadvantage is that the accuracy of the prediction depends largely on the experts' knowledge. Therefore, it is crucial to carefully select the panel of experts that reflect experience and understanding of offshore operations for the case under consideration.

The risk evaluation tasks depend on the purpose of the quantitative risk assessment. The risk calculated is compared with the acceptance criteria set by the organization and/or policies and regulations that may vary region to region. Identification of possible risk reducing measures should also be performed throughout and as a part of the risk assessment process. One option will involve the identification of the model elements that have more influence in the final risk estimation.

At the end, the approach adopted in this work provided invaluable insights into the understanding of the various factors involved in the risk analysis related to occupational accidents in offshore operations and provided a methodology for its estimation. The holistic approach of the proposed model provides a more realistic representation of the factors influencing safety. The proposed approach allows each factor to be assessed separately and independently from others to evaluate its contribution to the overall safety. To this end, the proposed model will allow the implementation of specific correction measures to improve the overall safety. The probabilistic approach and the Monte Carlo simulations help to get a probabilistic outcome, where a range of all possible scenarios are included; such as: best average and worst. This will allow a more accurate deployment of resources to key elements in order to improve the overall safety to a particular desired condition. In summary, the proposed method is a useful tool for:

prediction of occupational accidents likelihood on a specific offshore platform, estimation of accident rate, allocator of resources to specific key entities of the model to produce optimal safety results as well as occupational risk estimator. Overall, such an approach worth pursuing and there is significant room to advance the state-of-the-art.

The following recommendations are proposed for future studies:

- The Risk Analysis portion of the model can be further improved by creating a numerical acceptance criteria tailored for each one of the severity classifications presented in this thesis. For example, ALARP triangles can be developed for major injury, over three day injury and dangerous occurrence independently. In order to fulfill this task, detailed accident data as well as occupational safety guidelines have to compile to produce representative and useful risk estimation for each category.

- In order to produce reliable results during model application it is imperative that the data being collected for analysis describes the same safety performance indicator than the global data used for the model calibration.

- Further work can also be performed to assess and to identify the key elements of the model for a specific offshore platform and study the implication of the improvement of their specific reliability value and their impact in the overall risk analysis. This information can be crucial for a strategic deployment of site-specific or region-specific resources in order to reduce the overall risk.

- Further, this model can be used as a tool for identification of key elements of occupational accidents and overall risk reduction for any offshore facility. Further, it can be used as a cost estimator of deployment of resources to particular elements of the model in order to obtain desired results. Academic exercises of case specific platforms are recommended.

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Appendix I

Safety Performance Indicators –Summary of OGP Data for Offshore Operations (Contractors and Companies) from year 2000 to 2011.

Safety Performance Indicators – Summary of OGP data 2011

Region	Type	hours-worked	No. Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	15,455,000	0	7	6	11	0.00	0.45	1.55
	contractor	86,965,000	2	59	77	133	2.30	0.70	3.14
	subtotal offshore	102,420,000	2	66	83	144	1.95	0.66	2.88
Asia/ Australasia	company	29,308,000	0	5	11	21	0.00	0.17	1.26
	contractor	152,264,000	4	71	74	87	2.63	0.49	1.53
	subtotal offshore	181,572,000	4	76	85	108	2.20	0.44	1.50
Europe	company	28,753,000	0	27	8	46	0.00	0.94	2.82
	contractor	127,206,000	2	205	92	291	1.57	1.63	4.64
	subtotal offshore	155,959,000	2	232	100	337	1.28	1.50	4.30
FSU	company	8,889,000	0	6	3	3	0.00	0.67	1.40
	contractor	45,581,000	0	19	28	32	0.00	0.42	1.81
	subtotal offshore	54,470,000	0	25	31	35	0.00	0.46	1.67
Middle East	company	10,832,000	0	1	2	3	0.00	0.09	0.55
	contractor	45,988,000	0	12	12	42	0.00	0.26	1.43
	subtotal offshore	56,820,000	0	13	14	45	0.00	0.23	1.27
North America	company	10,977,000	0	8	7	6	0.00	0.73	1.91
	contractor	42,022,000	0	18	30	47	0.00	0.43	2.26
	subtotal offshore	52,999,000	0	26	37	53	0.00	0.49	2.19
South America	company	26,470,000	1	18	8	55	3.78	0.72	3.10
	contractor	145,768,000	4	102	180	311	2.74	0.73	4.10
	subtotal offshore	172,238,000	5	120	188	366	2.90	0.73	3.94
	TOTAL 2011	776,478,000	13	558	538	1,088	1.67	0.74	2.83

Safety Performance Indicators – Summary of OGP data 2010

Region	Type	hours-worked	No Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	26,210,000	1	16	9	15	3.82	0.27	1.18
	contractor	158,558,000	8	46	94	156	5.05	0.34	1.92
	subtotal offshore	184,768,000	9	62	103	171	4.87	0.38	1.87
Asia/ Australasia	company	33,330,000	0	16	11	22	0.00	0.48	1.47
	contractor	232,947,000	5	70	125	166	2.15	0.32	1.57
	subtotal offshore	266,277,000	5	86	136	188	1.88	0.34	1.56
Europe	company	26,897,000	0	34	11	46	0.00	1.26	3.38
	contractor	115,879,000	0	169	118	262	0.00	1.46	4.74
	subtotal offshore	142,776,000	0	203	129	308	0.00	1.42	4.48
FSU	company	8,098,000	0	0	1	1	0.00	0.00	0.25
	contractor	35,813,000	0	24	22	31	0.00	0.67	2.15
	subtotal offshore	43,911,000	0	24	23	32	0.00	0.55	1.80
Middle East	company	78,665,000	0	29	11	40	0.00	0.37	1.02
	contractor	39,726,000	2	21	14	68	5.03	0.58	2.64
	subtotal offshore	118,391,000	2	50	25	108	1.69	0.44	1.56
North America	company	14,072,000	0	5	3	15	0.00	0.36	1.63
	contractor	41,591,000	12	24	33	53	28.85	0.87	2.93
	subtotal offshore	55,663,000	12	29	36	68	21.56	0.74	2.60
South America	company	28,454,000	0	14	9	24	0.00	0.49	1.65
	contractor	121,078,000	0	91	86	226	0.00	0.75	3.33
	subtotal offshore	149,532,000	0	105	95	250	0.00	0.70	3.01
	TOTAL 2010	961,318,000	28	559	547	1,125	2.91	0.61	2.35

Safety Performance Indicators – Summary of OGP data 2009

Region	Type	hours-worked	No. Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	24,947,000	1	8	5	22	4.01	0.36	1.44
	contractor	154,831,000	3	57	94	159	1.94	0.39	2.03
	subtotal offshore	179,778,000	4	65	99	181	2.22	0.38	1.94
Asia/ Australasia	company	25,256,000	0	15	7	16	0.00	0.59	1.50
	contractor	163,130,000	4	86	81	155	2.45	0.55	2.00
	subtotal offshore	188,386,000	4	101	88	171	2.12	0.56	1.93
Europe	company	27,292,000	0	33	11	50	0.00	1.21	3.54
	contractor	113,338,000	2	207	118	316	1.76	1.84	5.68
	subtotal offshore	140,630,000	2	240	129	366	1.42	1.72	5.24
FSU	company	3,086,000	0	0	0	1	0.00	0.00	0.32
	contractor	11,607,000	1	0	8	7	8.62	0.09	1.38
	subtotal offshore	14,693,000	1	0	8	8	6.81	0.07	1.16
Middle East	company	9,098,000	0	4	2	7	0.00	0.44	1.43
	contractor	63,533,000	0	21	17	70	0.00	0.33	1.70
	subtotal offshore	72,631,000	0	25	19	77	0.00	0.34	1.67
North America	company	13,015,000	0	5	13	10	0.00	0.38	2.15
	contractor	47,187,000	10	17	55	83	21.19	0.57	3.48
	subtotal offshore	60,202,000	10	22	68	93	16.61	0.53	3.21
South America	company	25,933,000	0	7	16	21	0.00	0.27	1.70
	contractor	108,063,000	1	7	114	188	0.93	0.66	3.45
	subtotal offshore	133,996,000	1	14	130	209	0.75	0.11	2.64
	TOTAL 2009	790,316,000	22	467	541	1,105	2.78	0.62	2.70

Safety Performance Indicators – Summary of OGP data 2008

Region	Type	hours-worked	No Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	23,780,000	0	11	10	20	0.00	0.46	1.72
	contractor	155,519,000	4	89	100	198	2.57	0.60	2.51
	subtotal offshore	179,299,000	4	100	110	218	2.23	0.58	2.41
Asia/ Australasia	company	28,939,000	0	7	6	22	0.00	0.24	1.21
	contractor	166,021,000	4	91	74	171	2.41	0.57	2.05
	subtotal offshore	194,960,000	4	98	80	193	2.05	0.52	1.92
Europe	company	27,269,000	0	28	5	77	0.00	1.03	4.03
	contractor	102,608,000	0	212	133	307	0.00	20.70	6.35
	subtotal offshore	129,877,000	0	240	138	384	0.00	1.85	5.87
FSU	company	6,484,000	0	0	2	2	0.00	0.00	0.62
	contractor	27,895,000	0	16	31	32	0.00	0.57	2.83
	subtotal offshore	34,379,000	0	16	33	34	0.00	0.47	2.41
Middle East	company	4,495,000	0	1	0	3	0.00	0.22	0.89
	contractor	23,418,000	1	23	9	42	4.27	1.02	3.20
	subtotal offshore	27,913,000	1	24	9	45	3.58	0.90	2.83
North America	company	10,489,000	0	5	9	8	0.00	0.48	2.10
	contractor	47,250,000	0	16	57	85	0.00	0.34	3.34
	subtotal offshore	57,739,000	0	21	66	93	0.00	0.36	3.12
South America	company	24,515,000	0	8	7	13	0.00	0.33	1.14
	contractor	107,629,000	8	90	92	208	7.43	0.91	3.70
	subtotal offshore	132,144,000	8	98	99	221	6.05	0.80	3.22
	TOTAL 2008	756,311,000	17	597	535	1188	2.25	0.81	3.09

Safety Performance Indicators – Summary of OGP data 2007

Region	Type	hours-worked	No. Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	16,126,000	0	6	10	35	0.00	0.37	3.28
	contractor	104,743,000	4	77	63	122	3.82	0.77	2.55
	subtotal offshore	120,869,000	4	83	73	157	3.31	0.72	2.62
Asia/ Australasia	company	22,480,000	1	9	12	23	4.45	0.44	2.00
	contractor	160,239,000	1	62	90	174	0.62	0.39	2.04
	subtotal offshore	182,719,000	2	71	102	197	1.09	0.40	2.04
Europe	company	29,648,000	0	31	11	54	0.00	1.05	3.25
	contractor	107,405,000	9	211	132	394	8.38	2.05	6.96
	subtotal offshore	137,053,000	9	242	143	448	6.57	1.83	6.14
FSU	company	3,454,000	0	0	2	0	0.00	0.00	0.58
	contractor	12,815,000	0	17	17	21	0.00	1.33	4.29
	subtotal offshore	16,269,000	0	17	19	21	0.00	1.04	3.50
Middle East	company	2,544,000	0	0	0	3	0.00	0.00	1.18
	contractor	19,913,000	1	17	10	31	5.02	0.90	2.96
	subtotal offshore	22,457,000	1	17	10	34	4.45	0.80	2.76
North America	company	13,231,000	0	2	10	17	0.00	0.15	2.19
	contractor	46,663,000	1	25	52	73	2.14	0.56	3.24
	subtotal offshore	59,894,000	1	27	62	90	1.67	0.47	3.01
South America	company	26,701,000	0	6	8	12	0.00	0.22	0.97
	contractor	83,995,000	2	53	85	122	2.38	0.65	3.12
	subtotal offshore	110,696,000	2	59	93	134	1.81	0.55	2.60
	TOTAL 2007	649,957,000	19	516	502	1081	2.92	0.82	3.26

Safety Performance Indicators – Summary of OGP data 2006

Region	Type	hours-worked	No Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	19,939,000	0	1	3	12	0.00	0.05	0.80
	contractor	117,487,000	0	67	82	163	0.00	0.57	2.66
	subtotal offshore	137,426,000	0	68	85	175	0.00	0.49	2.39
Asia/ Australasia	company	20,470,000	0	4	1	8	0.00	0.20	0.64
	contractor	125,959,000	4	63	45	128	3.18	0.53	1.91
	subtotal offshore	146,429,000	4	67	46	136	2.73	0.48	1.73
Europe	company	26,918,000	0	38	5	64	0.00	1.41	4.02
	contractor	93,865,000	1	238	109	360	1.07	2.55	7.56
	subtotal offshore	120,783,000	1	276	114	424	0.83	2.29	6.75
FSU	company	2,448,000	0	0	0	1	0.00	0.00	0.41
	contractor	18,453,000	0	31	16	44	0.00	1.68	4.93
	subtotal offshore	20,901,000	0	31	16	45	0.00	1.48	4.40
Middle East	company	6,870,000	0	3	2	13	0.00	0.44	2.64
	contractor	46,203,000	1	39	24	63	2.16	0.87	2.75
	subtotal offshore	53,073,000	1	42	26	76	1.88	0.81	2.73
North America	company	23,559,000	0	12	21	48	0.00	0.51	3.44
	contractor	53,958,000	2	32	87	123	3.71	0.63	4.52
	subtotal offshore	77,517,000	2	44	108	171	2.58	0.59	4.19
South America	company	38,277,000	0	103	16	17	0.00	2.69	1.74
	contractor	99,702,000	3	144	180	170	3.01	1.47	5.21
	subtotal offshore	137,979,000	3	247	196	187	2.17	1.81	4.59
	TOTAL 2006	694,108,000	11	775	591	1214	1.58	1.13	3.73

Safety Performance Indicators – Summary of OGP data 2005

Region	Type	hours-worked	No. Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	17,335,000	1	10	6	15	5.77	0.63	1.85
	contractor	97,981,000	1	72	86	189	1.02	0.75	3.59
	subtotal offshore	115,316,000	2	82	92	204	1.73	0.73	3.30
Asia/ Australasia	company	17,219,000	0	12	4	17	0.00	0.70	1.92
	contractor	90,328,000	3	56	55	152	3.32	0.65	2.97
	subtotal offshore	107,547,000	3	68	59	169	2.79	0.66	2.78
Europe	company	20,942,000	0	28	8	50	0.00	1.34	4.11
	contractor	74,152,000	1	165	63	292	1.35	2.24	7.03
	subtotal offshore	95,094,000	1	193	71	342	1.05	2.04	6.38
FSU	company	2,608,000	0	1	3	4	0.00	0.38	3.07
	contractor	27,526,000	1	11	8	49	3.63	0.44	2.51
	subtotal offshore	30,134,000	1	12	11	53	3.32	0.43	2.56
Middle East	company	10,116	0	10	1	11	0.00	0.99	2.17
	contractor	54,348,000	2	41	15	118	3.68	0.79	3.24
	subtotal offshore	54,358,116	2	51	16	129	3.68	0.98	3.64
North America	company	10,114,000	0	0	6	11	0.00	0.00	1.68
	contractor	36,737,000	0	21	56	65	0.00	0.57	3.87
	subtotal offshore	46,851,000	0	21	62	76	0.00	0.45	3.39
South America	company	14,800,000	0	67	0	26	0.00	4.53	6.28
	contractor	29,455,000	1	62	4	58	3.40	2.14	4.24
	subtotal offshore	44,255,000	1	129	4	84	2.26	2.94	4.93
	TOTAL 2005	493,555,116	10	556	315	1057	2.03	1.15	3.93

Safety Performance Indicators – Summary of OGP data 2004

Region	Type	hours-worked	No. Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	13,402,000	0	4	4	694	0.00	0.30	52.90
	contractor	113,419,000	8	106	55	230	7.05	1.01	5.20
	subtotal offshore	126,821,000	8	110	59	924	6.31	0.93	8.68
Asia/Australasia	company	27,248,000	0	15	8	27	0.00	0.55	2.34
	contractor	118,451,000	2	85	36	246	1.69	0.73	3.34
	subtotal offshore	145,699,000	2	100	44	273	1.37	0.70	2.88
Europe	company	25,495,000	0	30	5	99	0.00	1.18	5.26
	contractor	68,294,000	0	180	56	413	0.00	2.64	9.50
	subtotal offshore	93,789,000	0	210	61	512	0.00	2.24	8.35
FSU	company	2,399,000	0	2	1	5	0.00	0.83	3.33
	contractor	12,701,000	1	5	8	20	7.87	0.47	2.68
	subtotal offshore	15,100,000	1	7	9	25	6.62	0.53	2.78
Middle East	company	8,629,000	0	5	2	26	0.00	0.58	3.82
	contractor	45,514,000	4	43	10	92	8.79	1.03	3.27
	subtotal offshore	54,143,000	4	48	12	118	7.39	0.96	3.36
North America	company	11,911,000	0	12	6	20	0.00	1.01	3.19
	contractor	43,548,000	14	55	57	126	32.15	1.58	5.79
	subtotal offshore	55,459,000	14	67	63	146	25.24	1.46	5.23
South America	company	12,137,000	0	20	0	2	0.00	1.65	0.99
	contractor	28,045	3	76	4	33	10.70	2.82	4.66
	subtotal offshore	12,165,045	3	96	4	35	24.66	8.14	11.34
	TOTAL 2004	503,176,045	32	638	252	2033	6.36	1.33	5.87

Safety Performance Indicators – Summary of OGP data 2003

Region	Type	hours-worked	No. Fatalities	No. LWDCs	No.RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	16,825,000	0	8	4	14	0.00	0.48	1.55
	contractor	45,456,000	9	108	44	133	19.80	2.57	6.47
	subtotal offshore	62,281,000	9	116	48	147	14.45	2.01	5.14
Asia/Australasia	company	18,371,000	1	5	13	19	5.44	0.33	2.42
	contractor	110,335,000	2	60	48	168	1.81	0.56	2.63
	subtotal offshore	128,706,000	3	65	61	187	2.33	0.53	2.46
Europe	company	25,190,000	2	40	9	84	7.94	1.67	5.36
	contractor	73,746,000	1	213	61	553	1.36	2.90	11.23
	subtotal offshore	98,936,000	3	253	70	637	3.03	2.59	9.73
FSU	company	2,088,000	0	2	0	2	0.00	0.96	1.92
	contractor	7,821,000	0	2	8	11	0.00	0.26	2.69
	subtotal offshore	9,909,000	0	4	8	13	0.00	0.40	2.52
Middle East	company	13,649,000	0	6	4	8	0.00	0.44	1.32
	contractor	56,537,000	1	30	23	65	1.77	0.55	2.10
	subtotal offshore	70,186,000	1	36	27	73	1.42	0.53	1.95
North America	company	57,868,000	1	81	10	17	1.73	1.42	2.89
	contractor	88,705,000	5	86	55	126	5.64	1.03	5.43
	subtotal offshore	146,573,000	6	167	65	143	4.09	1.18	2.60
South America	company	2,290,000	0	0	1	1	0.00	0.00	0.94
	contractor	10,470,000	0	7	13	33	0.00	0.67	5.40
	subtotal offshore	12,760,000	0	7	14	34	0.00	0.55	4.31
	TOTAL 2003	529,351,000	22	648	293	1234	4.16	1.27	4.15

Safety Performance Indicators – Summary of OGP data 2002

Region	Type	hours-worked	No. Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	5,393,000	0	8	1	9	0.00	1.48	3.38
	contractor	36,134,000	2	74	24	122	5.53	2.10	6.31
	subtotal offshore	41,527,000	2	82	25	131	4.82	2.02	5.78
Asia/Australasia	company	17,756,000	0	9	12	17	0.00	0.51	2.78
	contractor	100,574,000	1	79	55	203	0.99	0.80	3.62
	subtotal offshore	118,330,000	1	88	67	220	0.85	0.75	3.18
Europe	company	25,718,000	3	42	10	76	11.66	1.75	5.72
	contractor	74,450,000	11	217	81	536	14.78	3.06	11.48
	subtotal offshore	100,168,000	14	259	91	612	13.98	2.73	9.74
sFSU	company	1,373,000	0	0	1	0	0.00	0.00	0.73
	contractor	4,389,000	0	4	1	3	0.00	0.91	1.82
	subtotal offshore	5,762,000	0	4	2	3	0.00	0.69	1.56
Middle East	company	9,829,000	0	7	3	9	0.00	0.71	2.00
	contractor	54,932,000	1	42	20	44	1.82	0.78	1.95
	subtotal offshore	64,761,000	1	49	23	53	1.54	0.77	1.95
North America	company	53,528,000	0	70	20	21	0.00	1.31	3.81
	contractor	100,281,000	4	172	105	200	3.99	1.76	8.30
	subtotal offshore	153,809,000	4	242	125	221	2.60	1.60	3.85
South America	company	1,513,000	0	1	1	3	0.00	0.66	3.75
	contractor	8,293,000	1	14	10	12	12.06	1.81	4.83
	subtotal offshore	9,806,000	1	15	11	15	10.20	1.63	4.28
	TOTAL 2002	494,163,000	23	739	344	1255	4.65	1.54	4.78

Safety Performance Indicators – Summary of OGP data 2001

Region	type	hours-worked	No Fatalities	No. LWDCs	No.RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	16,391,000	0	9	1	7	0.00	0.55	0.96
	contractor	51,142,000	4	113	18	107	7.82	2.29	4.57
	subtotal offshore	67,533,000	4	122	19	114	5.92	1.87	3.84
Asia/Australasia	company	18,171,000	0	10	14	19	0.00	0.55	2.49
	contractor	83,956,000	3	95	47	201	3.57	1.17	4.60
	subtotal offshore	102,127,000	3	105	61	220	2.94	1.06	3.81
Europe	company	19,144,000	0	44	5	79	0.00	2.30	6.93
	contractor	80,454,000	4	294	47	673	4.97	3.70	13.33
	subtotal offshore	99,598,000	4	338	52	752	4.02	3.43	11.51
FSU	company	1,417,000	0	0	0	2	0.00	0.00	1.41
	contractor	3,278,000	2	3	2	11	61.01	1.53	5.49
	subtotal offshore	4,695,000	2	3	2	13	42.60	1.06	4.26
Middle East	company	7,832,000	0	3	0	13	0.00	0.38	2.88
	contractor	27,588,000	0	24	3	78	0.00	0.87	4.66
	subtotal offshore	35,420,000	0	27	3	91	0.00	0.76	3.42
North America	company	37,966,000	0	57	6	38	0.00	1.50	3.89
	contractor	68,149,000	6	114	37	276	8.80	1.76	8.85
	subtotal offshore	106,115,000	6	171	43	314	5.65	1.67	5.03
South America	company	1,402,000	0	0	0	1	0.00	0.00	0.72
	contractor	6,409,000	0	9	5	14	0.00	1.40	4.47
	subtotal offshore	7,811,000	0	9	5	15	0.00	1.15	3.71
	TOTAL 2001	423,299,000	19	775	185	1519	4.49	1.88	5.90

Safety Performance Indicators – Summary of OGP data 2000

Region	Type	hours-worked	No. Fatalities	No. LWDCs	No. RWDCs	No. MTCs	FAR	LTIF	TRIR
Africa	company	14,309,000	0	15	2	9	0.00	1.05	1.11
	contractor	44,152,000	2	89	9	102	4.53	2.06	4.31
	subtotal offshore	58,461,000	2	104	11	111	3.42	1.81	3.90
Asia/ Australasia	company	16,549,000	1	25	13	26	12.05	1.63	4.30
	contractor	66,273,000	4	64	25	176	6.04	1.03	4.57
	subtotal offshore	82,822,000	5	89	38	202	6.04	1.13	4.03
Europe	company	20,174,000	0	44	31	99	0.00	2.18	8.99
	contractor	82,324,000	5	312	172	849	6.07	3.85	17.09
	subtotal offshore	102,498,000	5	356	203	948	4.88	3.52	14.75
FSU	company	1,129,000	0	0	0	0	0.00	0.00	0.00
	contractor	2,375,000	0	1	0	2	0.00	0.42	1.26
	subtotal offshore	3,504,000	0	1	0	2	0.00	0.29	0.86
Middle East	company	2,816,000	0	2	0	4	0.00	0.71	3.30
	contractor	11,818,000	1	35	0	22	8.46	3.05	5.42
	subtotal offshore	14,634,000	1	37	0	26	6.83	2.60	4.37
North America	company	35,007,000	1	76	7	27	2.86	2.20	4.48
	contractor	62,599,000	3	145	75	282	4.79	2.36	10.37
	subtotal offshore	97,606,000	4	221	82	309	4.10	2.31	6.31
South America	company	1,172,000	0	2	0	0	0.00	1.71	1.71
	contractor	3,395,000	0	7	1	15	0.00	2.06	6.77
	subtotal offshore	4,567,000	0	9	1	15	0.00	1.97	5.47
	TOTAL 2000	364,092,000	17	817	335	1613	4.67	2.29	7.64

Appendix II

Normalized survey responses for Influence Coefficients and Strength Values

The normalized survey responses have been calculated from Appendix 3.1 – Actual survey responses (Attwood 2006)

Key:

A: Americas

S: Asia

E: Europe, Middle East, and Africa

R: Regulator

U: Researcher

C: Contractor

O: Operator

.

Influence Coefficients

Respondent Characteristics	Respondent Region Category	A1 R	A2 R	A3 R	A4 R	A5 R	A6 R	A7 R	A8 R	A9 R	A10 R	A11 U	A12 U	A13 U	A14 U	A15 C
Influence on Training	Value place on life	0.28	0.44	0.41	0.53	0.31	0.47	0.47	0.33	0.50	0.45	0.50	0.57	0.44	0.40	0.33
	Price of oil	0.24	0.17	0.23	0.13	0.14	0.16	0.12	0.29	0.14	0.14	0.07	0.14	0.17	0.15	0.25
	Shareholder pressure	0.32	0.28	0.27	0.27	0.28	0.26	0.35	0.24	0.29	0.27	0.36	0.14	0.28	0.25	0.33
	Royalty regime	0.16	0.11	0.09	0.07	0.28	0.11	0.06	0.14	0.07	0.14	0.07	0.14	0.11	0.20	0.08
Influence on Procedures	Value place on life	0.28	0.50	0.33	0.47	0.33	0.23	0.50	0.32	0.53	0.45	0.50	0.63	0.32	0.36	0.35
	Price of oil	0.24	0.17	0.29	0.13	0.08	0.31	0.11	0.27	0.13	0.14	0.06	0.13	0.18	0.18	0.23
	Shareholder pressure	0.32	0.17	0.29	0.20	0.25	0.27	0.33	0.23	0.27	0.27	0.38	0.13	0.32	0.18	0.35
	Royalty regime	0.16	0.17	0.08	0.20	0.33	0.19	0.06	0.18	0.07	0.14	0.06	0.13	0.18	0.27	0.08
Influence on Safety Culture	Value place on life	0.28	0.50	0.39	0.47	0.32	0.23	0.53	0.30	0.50	0.45	0.53	0.63	0.40	0.40	0.32
	Price of oil	0.24	0.17	0.22	0.13	0.28	0.31	0.11	0.30	0.13	0.14	0.06	0.13	0.10	0.20	0.24
	Shareholder pressure	0.32	0.17	0.30	0.20	0.08	0.27	0.32	0.20	0.31	0.27	0.35	0.13	0.30	0.16	0.36
	Royalty regime	0.16	0.17	0.09	0.20	0.32	0.19	0.05	0.20	0.06	0.14	0.06	0.13	0.20	0.24	0.08

Influence Coefficient (Cont'd)

Respondent Characteristics	Respondent Region Category	A16 O	A17 O	A18 O	A19 O	S1 R	S2 R	S3 R	S4 C	S5 O	E1 R	E2 R	E3 R	E4 R	E5 R	E6 R
Influence on Training	Value place on life	0.37	0.44	0.39	0.41	0.40	0.44	0.37	0.45	0.42	0.47	0.40	0.50	0.47	0.39	0.42
	Price of oil	0.26	0.17	0.17	0.14	0.15	0.17	0.16	0.09	0.32	0.13	0.25	0.13	0.12	0.22	0.17
	Shareholder pressure	0.32	0.28	0.28	0.32	0.35	0.28	0.26	0.36	0.21	0.33	0.25	0.25	0.29	0.26	0.21
	Royalty regime	0.05	0.11	0.17	0.14	0.10	0.11	0.21	0.09	0.05	0.07	0.10	0.13	0.12	0.13	0.21
Influence on Procedures	Value place on life	0.44	0.39	0.39	0.41	0.39	0.56	0.37	0.43	0.44	0.50	0.53	0.63	0.47	0.45	0.42
	Price of oil	0.17	0.22	0.17	0.14	0.11	0.17	0.16	0.10	0.28	0.13	0.20	0.13	0.12	0.20	0.17
	Shareholder pressure	0.33	0.28	0.28	0.32	0.39	0.28	0.26	0.38	0.22	0.31	0.20	0.13	0.29	0.25	0.21
	Royalty regime	0.06	0.11	0.17	0.14	0.11	0.00	0.21	0.10	0.06	0.06	0.07	0.13	0.12	0.10	0.21
Influence on Safety Culture	Value place on life	0.47	0.39	0.42	0.41	0.35	0.56	0.33	0.43	0.47	0.62	0.53	0.63	0.53	0.41	0.32
	Price of oil	0.16	0.22	0.16	0.14	0.15	0.17	0.14	0.10	0.24	0.15	0.20	0.13	0.11	0.18	0.26
	Shareholder pressure	0.32	0.28	0.26	0.32	0.35	0.28	0.33	0.38	0.24	0.15	0.20	0.13	0.26	0.23	0.26
	Royalty regime	0.05	0.11	0.16	0.14	0.15	0.00	0.19	0.10	0.06	0.08	0.07	0.13	0.11	0.18	0.16

Influence Coefficient (Cont'd)

Respondent Characteristics	Respondent Region Category	E7 R	E8 R	E9 R	E10 U	E11 C	E12 C	E13 C	E14 C	E15 C	E16 C	E17 O	E18 O	E19 O	E20 O	E21 O
Influence on Training	Value place on life	0.44	0.44	0.33	0.62	0.57	0.45	0.38	0.20	0.44	0.57	0.47	0.33	0.57	0.44	0.50
	Price of oil	0.17	0.17	0.25	0.15	0.14	0.27	0.14	0.40	0.17	0.14	0.12	0.33	0.14	0.17	0.33
	Shareholder pressure	0.28	0.28	0.29	0.15	0.14	0.18	0.33	0.20	0.28	0.21	0.35	0.17	0.21	0.28	0.17
	Royalty regime	0.11	0.11	0.13	0.08	0.14	0.09	0.14	0.20	0.11	0.07	0.06	0.17	0.07	0.11	0.00
Influence on Procedures	Value place on life	0.44	0.29	0.40	0.62	0.57	0.42	0.36	0.20	0.42	0.39	0.47	0.40	0.57	0.39	0.50
	Price of oil	0.17	0.21	0.20	0.15	0.14	0.29	0.14	0.40	0.21	0.33	0.13	0.20	0.14	0.17	0.33
	Shareholder pressure	0.28	0.36	0.30	0.15	0.14	0.21	0.36	0.20	0.26	0.17	0.33	0.20	0.21	0.30	0.17
	Royalty regime	0.11	0.14	0.10	0.08	0.14	0.08	0.14	0.20	0.11	0.11	0.07	0.20	0.07	0.13	0.00
Influence on Safety Culture	Value place on life	0.39	0.30	0.38	0.64	0.57	0.56	0.36	0.29	0.45	0.46	0.43	0.40	0.57	0.36	0.67
	Price of oil	0.17	0.26	0.19	0.14	0.14	0.17	0.14	0.35	0.18	0.31	0.14	0.20	0.14	0.18	0.22
	Shareholder pressure	0.33	0.37	0.29	0.14	0.14	0.17	0.36	0.18	0.27	0.15	0.36	0.20	0.21	0.27	0.11
	Royalty regime	0.11	0.07	0.14	0.07	0.14	0.11	0.14	0.18	0.09	0.08	0.07	0.20	0.07	0.18	0.00

Respondent Characteristics	Respondent Region Category	A1 R	A2 R	A3 R	A4 R	A5 R	A6 R	A7 R	A8 R	A9 R	A10 R	A11 U	A12 U	A13 U	A14 U	A15 C
Overall layer	External	0.26	0.20	0.32	0.29	0.22	0.28	0.20	0.29	0.21	0.29	0.25	0.06	0.47	0.24	0.29
	Corporate	0.43	0.40	0.41	0.36	0.43	0.28	0.50	0.33	0.64	0.38	0.33	0.35	0.33	0.38	0.38
	Direct	0.30	0.40	0.27	0.36	0.35	0.44	0.30	0.38	0.14	0.33	0.42	0.59	0.20	0.38	0.33
External Elements	Financial	0.56	0.33	0.58	0.45	0.38	0.47	0.44	0.36	0.78	0.44	0.42	0.50	0.58	0.44	0.43
	Value Placed on Life	0.44	0.67	0.42	0.55	0.62	0.53	0.56	0.64	0.22	0.56	0.58	0.50	0.42	0.56	0.57
Financial Elements	Price of Oil	0.35	0.33	0.41	0.40	0.24	0.35	0.11	0.41	0.50	0.35	0.14	0.33	0.41	0.27	0.35
	Shareholder pressure	0.41	0.33	0.47	0.33	0.38	0.24	0.78	0.35	0.36	0.30	0.71	0.33	0.29	0.27	0.53
	Royalty regime	0.24	0.33	0.12	0.27	0.38	0.41	0.11	0.24	0.14	0.35	0.14	0.33	0.29	0.47	0.12
Corporate layer	Safety Culture	0.36	0.29	0.33	0.36	0.43	0.31	0.38	0.35	0.32	0.40	0.41	0.29	0.24	0.38	0.43
	Training	0.32	0.33	0.33	0.32	0.30	0.34	0.31	0.35	0.36	0.32	0.27	0.33	0.33	0.33	0.33
	Safety Procedures	0.32	0.38	0.33	0.32	0.26	0.34	0.31	0.30	0.32	0.28	0.32	0.38	0.43	0.29	0.24
Direct layer	Behavioural	0.26	0.22	0.22	0.22	0.25	0.23	0.29	0.25	0.29	0.23	0.26	0.20	0.18	0.20	0.23
	Capability	0.18	0.19	0.22	0.20	0.20	0.20	0.17	0.20	0.23	0.23	0.21	0.18	0.25	0.17	0.21
	Weather	0.13	0.14	0.17	0.18	0.15	0.15	0.14	0.20	0.13	0.18	0.18	0.18	0.14	0.20	0.18
	Safety design	0.23	0.22	0.22	0.18	0.20	0.25	0.23	0.20	0.26	0.18	0.18	0.20	0.29	0.23	0.18
	PPE	0.21	0.22	0.17	0.22	0.20	0.18	0.17	0.15	0.10	0.20	0.18	0.25	0.14	0.20	0.21
Behavioural elements	Attitude	0.53	0.47	0.50	0.53	0.59	0.56	0.59	0.56	0.56	0.47	0.56	0.50	0.62	0.57	0.50
	Motivation	0.47	0.53	0.50	0.47	0.41	0.44	0.41	0.44	0.44	0.53	0.44	0.50	0.38	0.43	0.50
Capability elements	Physical	0.33	0.38	0.44	0.42	0.47	0.44	0.38	0.47	0.44	0.43	0.36	0.47	0.38	0.43	0.44
	Mental	0.67	0.62	0.56	0.58	0.53	0.56	0.62	0.53	0.56	0.57	0.64	0.53	0.62	0.57	0.56
Physical Capability	Lack of fatigue	0.45	0.37	0.35	0.38	0.43	0.37	0.40	0.38	0.38	0.36	0.43	0.29	0.36	0.38	0.38
	coordination	0.32	0.26	0.39	0.29	0.33	0.30	0.35	0.33	0.29	0.32	0.33	0.29	0.21	0.38	0.33
	Fitness	0.23	0.37	0.26	0.33	0.24	0.33	0.25	0.29	0.33	0.32	0.24	0.43	0.43	0.24	0.29
Mental Capability	Knowledge	0.53	0.53	0.56	0.60	0.46	0.56	0.56	0.53	0.53	0.47	0.44	0.50	0.62	0.62	0.56
	Intelligence	0.47	0.47	0.44	0.40	0.54	0.44	0.44	0.47	0.47	0.53	0.56	0.50	0.38	0.38	0.44

Respondent Characteristics	Respondent Region Category	A16 O	A17 O	A18 O	A19 O	S1 R	S2 R	S3 R	S4 C	S5 O	E1 R	E2 R	E3 R	E4 R	E5 R	E6 R
Overall layer	External	0.19	0.22	0.22	0.34	0.32	0.17	0.11	0.13	0.29	0.13	0.11	0.06	0.33	0.25	0.29
	Corporate	0.50	0.33	0.39	0.34	0.32	0.39	0.53	0.33	0.47	0.44	0.44	0.47	0.33	0.40	0.48
	Direct	0.31	0.44	0.39	0.31	0.36	0.44	0.37	0.53	0.24	0.44	0.44	0.47	0.33	0.35	0.24
External Elements	Financial	0.56	0.55	0.36	0.29	0.43	0.88	0.30	0.50	0.22	0.29	0.27	0.09	0.44	0.33	0.40
	Value Placed on Life	0.44	0.45	0.64	0.71	0.57	0.13	0.70	0.50	0.78	0.71	0.73	0.91	0.56	0.67	0.60
Financial Elements	Price of Oil	0.45	0.00	0.27	0.21	0.31	0.29	0.27	0.17	0.33	0.33	0.33	0.09	0.25	0.33	0.44
	Shareholder pressure	0.36	0.58	0.45	0.57	0.44	0.53	0.64	0.67	0.33	0.50	0.33	0.45	0.42	0.50	0.28
	Royalty regime	0.18	0.42	0.27	0.21	0.25	0.18	0.09	0.17	0.33	0.17	0.33	0.45	0.33	0.17	0.28
Corporate layer	Safety Culture	0.38	0.36	0.31	0.36	0.33	0.33	0.41	0.30	0.45	0.30	0.30	0.33	0.36	0.37	0.36
	Training	0.29	0.36	0.35	0.32	0.29	0.33	0.36	0.33	0.35	0.35	0.30	0.33	0.32	0.21	0.36
	Safety Procedures	0.33	0.27	0.35	0.32	0.38	0.33	0.23	0.37	0.20	0.35	0.39	0.33	0.32	0.42	0.27
Direct layer	Behavioural	0.30	0.23	0.20	0.26	0.24	0.32	0.26	0.31	0.27	0.21	0.24	0.24	0.22	0.32	0.26
	Capability	0.24	0.21	0.20	0.24	0.21	0.18	0.26	0.31	0.24	0.24	0.18	0.24	0.20	0.25	0.26
	Weather	0.12	0.21	0.20	0.06	0.16	0.18	0.11	0.08	0.15	0.17	0.12	0.06	0.20	0.14	0.12
	Safety design	0.18	0.18	0.18	0.21	0.18	0.32	0.20	0.15	0.21	0.14	0.24	0.24	0.22	0.11	0.18
	PPE	0.15	0.18	0.22	0.24	0.21	0.00	0.17	0.15	0.12	0.24	0.24	0.24	0.17	0.18	0.18
Behavioural elements	Attitude	0.56	0.57	0.56	0.62	0.50	0.00	0.56	0.50	0.47	0.50	0.50	0.50	0.53	0.44	0.38
	Motivation	0.44	0.43	0.44	0.38	0.50	1.00	0.44	0.50	0.53	0.50	0.50	0.50	0.47	0.56	0.63
Capability elements	Physical	0.44	0.38	0.43	0.33	0.31	0.00	0.38	0.40	0.25	0.38	0.38	0.20	0.44	0.36	0.43
	Mental	0.56	0.62	0.57	0.67	0.69	1.00	0.62	0.60	0.75	0.62	0.62	0.80	0.56	0.64	0.57
Physical Capability	Lack of fatigue	0.39	0.36	0.36	0.38	0.38	0.35	0.38	0.35	0.39	0.47	0.40	0.40	0.37	0.44	0.33
	coordination	0.28	0.32	0.32	0.33	0.33	0.45	0.33	0.39	0.39	0.26	0.35	0.40	0.33	0.31	0.33
	Fitness	0.33	0.32	0.32	0.29	0.29	0.20	0.29	0.26	0.22	0.26	0.25	0.20	0.30	0.25	0.33
Mental Capability	Knowledge	0.53	0.43	0.53	0.59	0.47	0.64	0.53	0.83	0.50	0.53	0.64	0.43	0.50	0.47	0.38
	Intelligence	0.47	0.57	0.47	0.41	0.53	0.36	0.47	0.17	0.50	0.47	0.36	0.57	0.50	0.53	0.62

Respondent Characteristics	Respondent Region Category	E7 R	E8 R	E9 R	E10 U	E11 C	E12 C	E13 C	E14 C	E15 C	E16 C	E17 O	E18 O	E19 O	E20 O	E21 O
Overall layer	External	0.11	0.22	0.29	0.33	0.32	0.17	0.33	0.17	0.30	0.12	0.29	0.13	0.13	0.13	0.07
	Corporate	0.44	0.43	0.38	0.33	0.36	0.50	0.48	0.50	0.43	0.47	0.47	0.50	0.38	0.50	0.67
	Direct	0.44	0.35	0.33	0.33	0.32	0.33	0.19	0.33	0.26	0.41	0.24	0.38	0.50	0.38	0.27
External Elements	Financial	0.30	0.50	0.43	0.43	0.17	0.29	0.57	0.63	0.31	0.70	0.47	0.27	0.50	0.38	0.20
	Value Placed on Life	0.70	0.50	0.57	0.57	0.83	0.71	0.43	0.38	0.69	0.30	0.53	0.73	0.50	0.62	0.80
Financial Elements	Price of Oil	0.33	0.40	0.33	0.00	0.33	0.38	0.25	0.40	0.33	0.43	0.31	0.50	0.33	0.00	0.17
	Shareholder pressure	0.44	0.40	0.47	0.50	0.33	0.25	0.40	0.30	0.39	0.33	0.50	0.25	0.50	0.62	0.83
	Royalty regime	0.22	0.20	0.20	0.50	0.33	0.38	0.35	0.30	0.28	0.24	0.19	0.25	0.17	0.38	0.00
Corporate layer	Safety Culture	0.38	0.37	0.38	0.31	0.38	0.38	0.38	0.35	0.38	0.33	0.36	0.37	0.24	0.43	0.33
	Training	0.33	0.37	0.29	0.35	0.29	0.31	0.31	0.35	0.31	0.33	0.36	0.33	0.36	0.29	0.33
	Safety Procedures	0.29	0.26	0.33	0.35	0.33	0.31	0.31	0.31	0.31	0.33	0.28	0.30	0.40	0.29	0.33
Direct layer	Behavioural	0.26	0.27	0.27	0.20	0.36	0.26	0.26	0.23	0.24	0.27	0.22	0.24	0.22	0.26	0.35
	Capability	0.23	0.27	0.18	0.23	0.18	0.17	0.21	0.23	0.22	0.19	0.22	0.22	0.22	0.17	0.17
	Weather	0.15	0.05	0.09	0.10	0.11	0.20	0.13	0.17	0.14	0.16	0.22	0.16	0.18	0.17	0.13
	Safety design	0.18	0.19	0.24	0.17	0.25	0.23	0.21	0.20	0.22	0.19	0.22	0.22	0.20	0.23	0.22
	PPE	0.18	0.22	0.21	0.30	0.11	0.14	0.21	0.17	0.19	0.19	0.11	0.16	0.18	0.17	0.13
Behavioural elements	Attitude	0.50	0.56	0.62	0.00	0.57	0.56	0.50	0.50	0.62	0.50	0.54	0.47	0.50	0.00	0.57
	Motivation	0.50	0.44	0.38	1.00	0.43	0.44	0.50	0.50	0.38	0.50	0.46	0.53	0.50	1.00	0.43
Capability elements	Physical	0.42	0.41	0.33	0.00	0.36	0.43	0.44	0.00	0.43	0.22	0.31	0.40	0.41	0.00	0.30
	Mental	0.58	0.59	0.67	1.00	0.64	0.57	0.56	1.00	0.57	0.78	0.69	0.60	0.59	1.00	0.70
Physical Capability	Lack of fatigue	0.39	0.43	0.50	0.43	0.42	0.39	0.42	0.36	0.33	0.33	0.47	0.38	0.36	0.37	0.21
	coordination	0.33	0.30	0.25	0.26	0.29	0.35	0.33	0.32	0.33	0.38	0.26	0.33	0.36	0.32	0.36
	Fitness	0.28	0.26	0.25	0.30	0.29	0.26	0.25	0.32	0.33	0.29	0.26	0.29	0.27	0.32	0.43
Mental Capability	Knowledge	0.53	0.63	0.50	0.47	0.44	0.60	0.50	0.62	0.53	0.53	0.64	0.53	0.64	0.44	0.54
	Intelligence	0.47	0.38	0.50	0.53	0.56	0.40	0.50	0.38	0.47	0.47	0.36	0.47	0.36	0.56	0.46

Appendix III

MATLAB code to solve seven unknown reliabilities of the Reliability Model.

```
clc;

clear all;


A=[0.9829      0.9823 0.9353 0.9962 0.9808 0.9723 0.976

0.9661 0.9656 0.8849 0.9776 0.9659 0.9503 0.9597

0.9408 0.9517 0.8422 0.9707 0.9573 0.9334 0.941

0.9182 0.9409 0.7995 0.9597 0.9488 0.922   0.9221

0.8802 0.9283 0.763   0.9475 0.934   0.8991 0.8723

0.8658 0.9162 0.735   0.9363 0.9181 0.8842 0.8508

0.8553 0.9086 0.7054 0.917   0.9061 0.8658 0.8307

0.8438 0.8997 0.6785 0.9016 0.894   0.8527 0.8192

0.8332 0.8912 0.6528 0.8911 0.8816 0.839   0.8051

0.8247 0.8828 0.6298 0.886   0.8743 0.825   0.7935

0.8165 0.8759 0.6101 0.8781 0.8674 0.8135 0.7803

0.8084 0.8691 0.5905 0.8702 0.8606 0.8021 0.7672

];

n=length(A(:,1));

m=length(A(1,:));

tol=10^-4;

B=zeros(n,m);
```

```
%mean values inputs
a1=.33; a2=.3; a3=.37; a4=.33; a5=.3; a6=.37; a7=.18; a8=.27; a9=.12; a10=.43;
a11=0.19;
a12=.26; a13=.12; a14=.43; a15=.18; a16=.25; a17=.13; a18=.44; a19=.36; a20=.3;
a21=.34;a22=.34;
a23=.3; a24=.36; a25=.31; a26=.32; a27=.37; a28=.32; a29=.33; a30=.35; a31=.31;
a32=.32; a33=.37;
v=zeros(1,7)+.98;

Delx=.0005;
sss=4;
upb=[.99,.99,.99,.99,0.99,.99,.99]; % the result of previous data (before updating), for
example here up to 2009. This helps to solve the problem quicker

for j=1:n
   if j>1
      upb=B(j-1,:);
   end

   Cap=0;
   vexf=zeros(1,7);
   while Cap<1000
```

```
Cap=Cap+1;
lob=upb-sss*Delx;
er=1000;
erv=zeros(7,1);
vcal=zeros(7,1);
vex=zeros(7,1);

for i1=lob(1):Delx:upb(1)
  for i2=lob(2):Delx:upb(2)
    for i3=lob(3):Delx:upb(3)
      for i4=lob(4):Delx:upb(4)
        for i5=lob(5):Delx:upb(5)
          for i6=lob(6):Delx:upb(6)
            for i7=lob(7):Delx:upb(7)
              esum=0;
              for i=1:m


                Rw=i1; Rcoo=i2; Ri=i3;Rpo=i4;Rsp=i5;Rrr=i6; Rvl=i7;
                Rt=Rpo*a7+Rsp*a8+Rrr*a9+Rvl*a10;
                Rpr=Rpo*a11+Rsp*a12+Rrr*a13+Rvl*a14;
                Rsc=Rpo*a15+Rsp*a16+Rrr*a17+Rvl*a18;
```

```
    Rf=Rt*a22+Rpr*a23+Rsc*a24;

    Rlf=Rt*a25+Rpr*a26+Rsc*a27;

    Rk=Rt*a19+Rpr*a20+Rsc*a21;

    Rp=(1-(1-Rf)^(0.29)*(1-Rlf)^(0.38)*(1-Rcoo)^(.33));

    Rme=(1-(1-Rk)^(.54)*(1-Ri)^(.46));

    Rc=(Rp)^(.36)*(Rme)^(.64);

    Ra=Rt*a1+Rpr*a2+Rsc*a3;

    Rm=Rt*a4+Rpr*a5+Rsc*a6;

    Rb=(1-(1-Ra)^(.49)*(1-Rm)^(.51));

    Rppe=Rt*a28+Rpr*a29+Rsc*a30;

    Rsd=Rt*a31+Rpr*a32+Rsc*a33;

    wea=Rw^.15;

    saf=Rsd^.21;

    per=Rppe^.18;

    beh=Rb^.25;

    capa=Rc^.21;

    Rcal=wea*saf*per*beh*capa;

    vcal(i)=wea*saf*per*beh*capa;

    esum=esum+(vcal(i)-A(j,i))^2;


end;

if esum< er
```

```
                        er=esum;
                        vex=[i1,i2,i3,i4,i5,i6,i7];
                      end
                    end
                  end
                end
              end
            end
          end
        end

        if (vex<upb)&(vex>lob)
          vexf=vex;
          break;
        else
          upb=min(upb,vex);
          upb;
        end
        if (vex==upb)
          upb=upb+Delx*3;
        end
        esum;
```

```
        Cap;
    end
    vex;
    vexf;
    B(j,:)=vexf;
end

B
```

Appendix IV

MATLAB code to find two parameter Weibull distributions for each of the seven reliability elements that require direct input.

```
clc;
clear all;
A=[1    0.9735
2       0.9525
3       0.934
4       0.917
5       0.89
6       0.874
7       0.858
8       0.845
9       0.8325
10      0.821
11      0.81
12      0.801
];
n=length(A(:,1));
te=0;
bet=0;
```

```
cap=0;
tel=60;
bel=.7;
lbd=[tel,bel];
delt=.01;
delb=.001;
del=[delt,delb];
ss=50;
ubd=lbd+ss*del;
wei=[0,0];
erm=1e-4;
while cap<1000
   cap=cap+1;
   er=exp(30);
   lbd=ubd-del*ss;
   for i=lbd(1):del(1):ubd(1)
      for j=lbd(2):del(2):ubd(2)
         ers=0;
         for ij=1:n
            ers=ers+(A(ij,2)-(exp(-(A(ij,1)/i)^j)))^2;
         end
         if ers< er
```

```
            er=ers;
            te=i;
            bet=j;
            wei=[te,bet];
        end
    end
end
if (wei<ubd)&(wei>lbd)
        wei
```