SAFETY PERFORMANCE MEASUREMENT FRAMEWORK FOR OFFSHORE OIL AND GAS PLATFORMS IN MALAYSIA

DANIEL TANG KUOK HO

FACULTY OF ENGINEEERING
UNIVERSITY OF MALAYA
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SAFETY PERFORMANCE MEASUREMENT FRAMEWORK FOR OFFSHORE OIL AND GAS PLATFORMS IN MALAYSIA

ABSTRACT

The Macondo blowout in the Gulf of Mexico on the 20th April 2010 which caused 11 fatalities and numerous serious injuries turned attention again to safety of offshore oil and gas activities. Findings of the US Chemical Safety Hazard Investigation Board pointed to a lack of focus on process safety addressing major accident hazards, over-reliance on lagging indicators and overemphasis on personal safety. The findings also highlighted the use of both leading and lagging safety indicators has great potential in major accident prevention.

Safety management on offshore installations is divided into process and personal safety, leading to fragmented safety performance measurement which overemphasizes on personal safety and the lagging aspects of process safety. From analysis of offshore accident data, the EU Commission recommended pooling of data to provide well-rounded picture of offshore safety, inclusion of near misses in accident databases, and common formatting to facilitate data and experience sharing.

This study presents a comprehensive safety performance measurement framework for offshore oil and gas platforms in Malaysia which combines both leading and lagging safety indicators to monitor major aspects of process and personal safety. It identifies 70 leading and lagging safety indicators grouped under 14 safety factors most pertinent to offshore oil and gas platforms via literature review and inputs of industrial practitioners. It stages an integrative approach to unify the relevant offshore safety indicators from past studies and systematically apply them for performance measurement.

The first phase of the study involved compilation of a list of indicators and development of questionnaire to gauge the perception of safety and health practitioners in 10 major oil and gas companies in Malaysia on the importance of the indicators and the perceived risk of failing to observe the indicators. The second phase involved statistical analyses of the survey data to yield descriptive statistics of the indicators, hence the safety factors, as well as the correlations between the safety factors demonstrated via factor analyses, hierarchical clustering and Pearson correlation. Weights of the safety indicators were also derived in this phase.

The third phase of the study centered on development and validation of the safety performance framework. The framework consists of two components, i.e. a scoring system to generate the scores of the respective safety factors, hence the overall safety score of an offshore installation, as well as a fuzzy inference system to generate a composite safety performance index based on scores of the safety factors and the rules established by safety experts. The framework functions to pull safety data together and presents them in a common format which is responsive to experience gained, emergence of new indicators and changes in performance targets and standards. An alternative architecture of the fuzzy inference system with intermediate models of correlated safety factors was also proposed to simplify rule-setting of fuzzy inference system.

The framework was finally validated against facility status reports and actual lagging performance of offshore platforms. The validation demonstrated reliability and applicability of the framework for offshore safety performance measurement, reporting and benchmarking. The findings showed the ability of the framework to highlight major contributors of offshore incidents, demonstrate interactions between safety factors, monitor well-being of platform's safety management system and reveal causation of physical safety system failure.

Keywords: Offshore; platforms; safety performance; indicators; framework

RANGKA PENILAIAN PRESTASI KESELAMATAN UNTUK PELANTAR MINYAK DAN GAS LUAR PESISIR DI MALAYSIA

ABSTRAK

Letupan Macondo di Teluk Mexico pada 20^{hb} April 2010 yang menyebabkan 11 kematian dan beberapa kecederaan serius telah sekali lagi mengalihkan perhatian terhadap keselamatan aktiviti minyak dan gas luar pesisir. Hasil siasatan Lembaga Penyiasatan Bahaya Keselamatan Kimia Amerika Syarikat mendapati kekurangan fokus terhadap keselamatan proses yang menekankan kebahayaan kemalangan besar, serta penumpuan yang berlebihan terhadap penunjuk 'lagging' dan keselamatan peribadi. Penemuan tersebut turut mencadangkan penggunaan kedua-dua penunjuk 'leading' dan 'lagging' berpotensi mencegah kemalangan serius.

Pengurusan keselamatan pemasangan luar pesisir boleh diklasifikasikan kepada keselamatan proses dan keselamatan peribadi. Hal ini menyebabkan pembahagian penilaian prestasi keselamatan yang lebih menekankan keselamatan peribadi dan aspek keselamatan proses berasaskan akibat (lagging). Berdasarkan analisis data kemalangan luar pesisir, Suruhanjaya EU mencadangkan penyatuan data untuk memberi gambaran keselamatan luar pensisir yang lebih sempurna di mana kejadian nyaris turut dimasukkan dalam pangkalan data. Suruhanjaya EU turut mencadangkan penggunaan format lazim untuk memudahkan perkongsian data dan pengalaman.

Kajian ini membentangkan rangka penilaian prestasi keselamatan komprehensif untuk pelantar minyak dan gas luar pesisir yang menggabungkan penunjuk 'leading' dan 'lagging' bagi pemantauan aspek-aspek yang berkenaan dengan keselamatan proses serta keselamatan peribadi. Rangka ini mengenalpasti 70 keselamatan penunjuk 'leading' dan

‘lagging’ yang dikelompokkan di bawah 14 faktor keselamatan pelantar minyak dan gas luar pesisir melalui tinjauan literatur dan input daripada pengamal industri. Rangka ini turut mengemukakan suatu pendekatan bersepadu yang menggabungkan penunjuk keselamatan luar pesisir daripada kajian-kajian sebelum ini dan mengaplikasi pendekatan tersebut secara sistematik untuk penilaian prestasi.

Fasa pertama kajian ini melibatkan kompilasi penunjuk dan pembinaan soal selidik untuk memantau pendapat pengamal industri di 10 syarikat minyak dan gas di Malaysia terhadap kepentingan penunjuk dan risiko akibat kegagalan mematuhi penunjuk tersebut. Fasa kedua kajian ini melibatkan analisis statistik data yang dikumpul melalui kaji selidik. Analisis statistik merangkumi statistik perihalan penunjuk dan faktor keselamatan, serta korelasi antara faktor keselamatan melalui analisis faktor, analisis gugus, dan korelasi Pearson. Fasa ini turut menghasilkan pemberat untuk penunjuk keselamatan.

Fasa ketiga kajian ini tertumpu kepada pembinaan dan pengesahan rangka penilaian prestasi keselamatan. Rangka ini terdiri daridapa dua komponen iaitu suatu sistem pengiraan skor untuk menjana skor bagi faktor keselamatan dan sejurusnya skor keseluruhan suatu pemasangan luar pesisir, serta suatu sistem inferens fuzzy yang menjanakan indeks komposit keselamatan berdasarkan skor faktor keselamatan dan peraturan yang disumbangkan oleh pakar-pakar keselamatan. Rangka ini turut menggabungkan data keselamatan dan mengemukakan data tersebut dalam format lazim yang peka terhadap pengalaman baru, kemunculan penunjuk baru serta perubahan sasaran dan piawai prestasi. Suatu rekaan sistem inferens fuzzy alternatif dengan model perantaraan yang berdasarkan faktor keselamatan yang berkorelasi turut dicadangkan untuk memudahkan penentuan peraturan bagi sistem inferens fuzzy.

Akhirnya, rangka ini disahkan melalui perbandingan dengan laporan status fasilitas dan prestasi sebenar pelantar luar pesisir berasaskan akibat. Pengesahan tersebut menunjukkan kebolehpercayaan dan kebolehgunaan rangka tercadang untuk penilaian prestasi keselamatan, pelaporan dan penandaan aras prestasi. Penemuan kajian ini juga menunjukkan kebolehan rangka ini untuk mengenalpasti faktor penyumbang utama kejadian luar pesisir, menonjolkan interaksi antara faktor keselamatan serta memautau keadaan sistem pengurusan keselamatan pelantar, disamping mendedahkan punca kegagalan sistem keselamatan fizikal.

Kata kunci: Luar pesisir; pelantar; prestasi keselamatan; penunjuk; rangka

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LIST OF SYMBOLS AND ABBREVIATIONS

AHP	:	Analytic hierarchy process
ALARP	:	As low as reasonably practicable
AlChE	:	American Institute of Chemical Engineers
ANFIS	:	Adaptive neuro-fuzzy inference system
ANSI	:	American National Standards Institute
API	:	American Petroleum Institute
AS/NZ	:	Australian Standard/ New Zealand Standard
ASP	:	Accident sequence precursor
BS	:	British Standard
CCPS	:	Centre for Chemical Process Safety
CoA	:	Center of area
CSB	:	Chemical Safety Board
dB(A)	:	A-weighted decibels
DSHA	:	Defined situations of hazard and accident
FEED	:	Front end engineering design
FIS	:	Fuzzy inference system
FMA	:	Factory and Machinery Act
FMEA	:	Failure mode and effect analysis
FMECA	:	Failure mode, effect and criticality analysis
GDP	:	Gross domestic product
HAZID	:	Hazard identification
HAZOP	:	Hazard and operability study
HEMP	:	Hazard and effect management process
HIRA	:	Hazard identification and risk assessment

HLI	:	High level indicator
HSE	:	Health and Safety Executive
HVAC	:	Heating ventilation and air conditioning
IAEA	:	International Atomic Energy Agency
ICI	:	Imperial Chemical Industries
ICP	:	Independent competent person
ILO	:	International Labour Organization
IOGP/ OGP	:	International Association of Oil and Gas Producers
IPIECA	:	International Petroleum Industry Environmental Conservation Association
ISM	:	Integrated Safety Model
ISO	:	International Organization for Standardization
KP3	:	Key Programme 3
KPI	:	Key performance indicator
LLI	:	Low level indicator
LOPC	:	Loss of primary containment
MATLAB	:	Matrix Laboratory
MCDM	:	Multi-criteria decision making
MF	:	Membership function
MOC	:	Management of Change
MoM	:	Mean of maxima
MWE	:	Management and work engagement
NOMAC	:	Nuclear Organisation and Management Analysis Concept
NRC	:	Nuclear Regulatory Commission
OECD	:	Organisation for Economic Co-operation and Development
OHSAS	:	Occupational Health and Safety Assessment Series

OSHA	:	Occupational Safety and Health Act
OTS	:	Operational condition safety
P&ID	:	Process and instrument diagram
PETRONAS	:	Petroliam National Berhad
PHA	:	Process hazard analysis
PSA	:	Probabilistic safety assessment
PSM	:	Process safety management
PSS	:	Production Sharing System
QRA	:	Quantitative risk assessment
RBFN	:	Radial basis function networks
RBPI	:	Risk-based performance indicator
REWI	:	Resilience-based early warning indicator
SCE	:	Safety critical elements
SD	:	Standard deviation
SI	:	Sensitivity index
SKI	:	Swedish Nuclear Power Inspectorate
SMART	:	Specific, measureable, achievable, relevant and time-bound
SPSS	:	Statistical Package for the Social Sciences
TEMPSC	:	Totally enclosed motor propelled survival craft
TOPSIS	:	Technique for order of preference by similarity to ideal solution
TPM	:	Total productive maintenance
UK	:	United Kingdom
US	:	United States
USCG	:	United States Coast Guard
WANO	:	World Association of Nuclear Operators
WPAM	:	Work Process Analysis Model

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

1.1 Introduction

Offshore oil and gas platforms are often regarded as high risk due to multiple internal and external hazards that workers thereon are potentially exposed to (Dahl & Olsen, 2013). In terms of external hazards, the platforms operate in challenging environment, constantly intimated by inclement weather and sea conditions. This gives rise to harsh working environment, complicated by remote locations of the platforms which could make seeking of help relatively more difficult than onshore facilities in times of distress (Høivik et al., 2009; Dahl & Olen, 2013).

Where internal hazards are concerned, workers often have to work within limited space with complex fittings on the platforms which presents ergonomic and occupational safety concerns such as trip and fall, falling objects, caught between objects, etc. (Øien & Sklet, 1999). Drilling as well as processing and storage of oil and gas on platforms expose workers to risks consisting of fire, explosion and well-blowout. Workers could also be subject to risks arising from facilities of the platforms such as power plant (OGP, 2013). While the offshore sectors strive to control the risks of offshore operations, recurrence of offshore incidents ranging from the Piper Alpha in 1988, the Petrobas P-36 in 2001 (OGP, 2010), to the Macondo Blowout in 2010 raise alarms that safety enhancement of offshore operations is vital. Between 1970 and 2007, a total of 553 offshore accidents were reported leading to 2171 fatalities (OGP, 2010).

In view of the risks associated with offshore operations, it is crucial to monitor the key safety performance areas to ascertain the proper functioning of various safety measures and risk management systems employed (API, 2010). It is a vital component of safety management system typified by the continual improvement cycle comprising policy, organizing, planning and implementation, evaluation and action for improvement (ILO, 2001). Being a central element of evaluation, an integrative performance measurement has an important role to provide an overview of whether all crucial aspects of a safety system are functioning optimally (ILO, 2001; Azadeh et al., 2008).

Effective safety performance measurement relies on good safety indicators to provide good indication of safety performance and early warnings of safety deviations (CCPS, 2011). Good safety indicators should comprise both leading indicators measuring the input or effort made in maintaining and promoting safety as well as lagging indicators measuring the outcomes (HSE, 2006). However, lagging indicators such as fatality and injury rates have conventionally received greater attention than leading indicators (Lauder, 2012) and this can potentially shift attention away from the underlying system defects and process deviations. The Esso Langford gas explosion was attributed partly to overemphasis on lagging indicators (Øien et al., 2011). The facility burst into fire while it celebrated its zero lost-time injury. Investigation of the accident revealed that major hazards in the facility were poorly managed and demonstrated that the use of lagging indicators alone were insufficient (Øien et al., 2011).

A wide range of indicators have been proposed by various safety agencies for monitoring of major industrial hazards (HSE, 2006; OECD, 2008; API, 2010; CCPS, 2010; OGP, 2011). However, a common problem of using off-the-shelf indicators is the lack of relevance to a particular industry or facility of interest, hence inefficiency in capturing the most pertinent aspects of safety performance related to the industry or facility (Swuste et al., 2016). Effective safety performance indicators should ideally be based on good understanding of the process, the risks and the critical 'barriers' (Reason, 1997). Previous studies of offshore safety indicators' development shared a general shortcoming in the sense that industrial experiences were insufficiently involved to generate a consensus of industrial- or facility-specific safety indicators (Sklet, 2006; Hopkins, 2009; Reiman and Pietikainen, 2012; Bhandari & Azevedo, 2013. Hopkins (2009).

With Malaysia holding the fourth-largest oil reserve and the third-largest natural gas reserve in the Asia-Pacific region, the oil, gas and energy sector contributes to about 20 percent of Malaysia's GDP (Malaysian Investment Development Authority, 2015). A well-developed safety system fitted to the unique regional characteristics and the processes involved is paramount to the Malaysian offshore oil and gas installations. This study marks an important endeavor to identify safety indicators most relevant to the offshore oil and gas platforms in Malaysia by tapping into the experiences of safety personnel in the Malaysian oil and gas sector.

The indicators identified serve as the basis of a good safety performance measurement system which provides an overall picture of how a facility performs in terms of safety or how the main factors governing safety of a facility are performing (HSE, 2006; CCPS, 2010). Currently, an obvious deficiency in facility level safety performance evaluation is that personal safety tends to be treated as a separate domain from process safety. Without an integrative approach, safety performance evaluation of an offshore oil and gas platform may not yield results which address the major aspects of safety.

Setting of targets and performance standards forms a crucial part of performance evaluation (OECD, 2008). This permits actual performance for each indicator to be compared against the targets or standards set, to determine if an indicator's performance is in line, ahead of or falling behind its expected performance. Commonly a traffic light system is used where red indicates non-compliance, amber indicates deviation which may represent isolated failure or incomplete system and green indicates compliance (HSE, 2009). Compliance status of the overarching safety factor can then be decided from the number of each traffic light color assigned for the indicators thereunder. Alternatively, scoring system can be used to determine the compliance status of the safety factors (Liou et al., 2007).

Advancement in fuzzy logic enables fuzzy inference system to be adopted in safety performance measurement where rules and experts' opinions can be captured to determine the overall compliance status of a facility (Sa'idi et al., 2014). Fuzzy inference system enables ambiguous or imprecise information to be processed, giving rise to a more reliable performance system and warning signal for the offshore oil and gas installations (Verma & Zakos, 2001). It also generates crisp outputs in relation to the compliance status of a platform. (Azadeh, 2008) which can potentially be used as composite index of safety performance.

Considering a lack of local expertise involvement in determining the indicators used for offshore safety performance measurement and the fragmented safety management practices, an integrative safety performance measurement framework for offshore oil and gas platforms in Malaysia is needed, tapping into advantages the fuzzy inference system provides in facilitating decision-making related to compliance status of the platforms. In contrast to the conventional traffic light compliance system, a scoring system provides greater flexibility for performance comparison and benchmarking, while the fuzzy inference system can generate a composite safety index of the platforms based on the rules set by the experts.

1.2 Problem Statement

In the Malaysian Oil and Gas Industry, safety indicators used to monitor offshore processes are derived largely from generic safety indicators published by the American Petroleum Institute (API) and the International Association of Oil and Gas Producers (IOGP), previously known in short as the OGP. The industry-wide indicators provide undifferentiated performance monitoring of oil and gas facilities with little consideration of regional- and facility- specific importance of the indicators, as well as requirements. Without linking the generic indicators to specific industrial experiences, the indicators will have limited ability in capturing the most important and relevant aspects of offshore oil and gas installations' safety performance (API, 2010; OGP, 2011; Podgorski, 2015).

Currently, there is a lack of studies to identify key safety indicators for offshore oil and gas platforms' operations in Malaysia. A search through established online scientific databases revealed virtually no results related to identification of indicators for offshore processes in Malaysia, and the closest match was studies related to sustainable production (Vijayalakshmi et al., 2013). With generic safety indicators adopted in safety performance measurement of the installations, the important aspects of platforms' safety may not be effectively captured to yield reliable earning warnings of critical deviations from operational norms. A lack of consensus in the indicators adopted by oil and gas companies gives rise to a barrier in information sharing and mutual learning, and benchmarking of safety performance (HSE, 2006; Hopkins, 2009).

In addition, overemphasis on lagging indicators measuring outcomes such as number and rate of incidents is common without due attention given to monitoring measures and efforts channeled to ensure safety on the installations. This overemphasis is evident in published corporate safety data focusing almost entirely on fatality and injury rates as the yardstick of safety with few revealing loss of containment and environmental leaks, thus giving inaccurate impression that actual safety performance of the installations are only tied to the few indicators mentioned (Petronas, 2013; Petronas, 2014; IOGP, 2015; Petronas, 2015; IOGP, 2016).

In the offshore sector, there is an obvious lack of integrative safety performance measurement approach where safety monitoring is often fragmented into the domains of process safety and personal safety (Sarshar et al., 2015; Petronas, 2015). Also, personal safety has been conventionally upheld over process safety. This study promulgates the need of an unbiased and comprehensive safety performance measurement integrating crucial aspects of the major safety domains to yield a more accurate picture of the safety performance of offshore oil and gas installations.

Safety performance measurement relies on performance standards and targets set for the key indicators. The practice varies among oil and gas companies due a lack of consensus on the key indicators used to measure the overall safety performance of Malaysian offshore oil and gas installations and the weights of the key indicators (Hassan & Abu Husain, 2013). Assigning weights to indicators is an optional practice and it is common that the indicators are treated as having equal weights without attempts to differentiate their relative importance (Petronas, 2013). To enable performance comparison, it is crucial to attain a certain level of consensus on the key indicators and the weights used. While it can be challenging at present to standardize performance targets across all oil and gas companies, having common indicators and weights reduce the variables in performance measurement, hence benchmarking (Ettorchi-Tardy et al., 2012). Often, expert's judgement translated into a series of rules is involved in evaluating and determining the overall safety performance of a platform. However, such judgement defers between practitioners and is dependent on the availability of experts (Klir & Yuan, 1995; Yang et al., 2011).

This study sees the importance of measuring the performance of major safety factors contributing to overall safety in benchmarking practices, thus enabling transverse performance comparison of the respective safety factors to be made in the future and, where relevant, reported. To enable benchmarking, a unifying framework of performance measurement is also necessary which can accommodate dynamic changes of performance standards and targets. As such, this study proposes a framework incorporating survey consensus to determine the safety scores of the respective safety factors, and the fuzzy inference system to indicate the overall performance of the installations from the safety scores of the respective safety factors. Fuzzy inference system enables the rules in decision-making to be stored, hence reducing the variability in decision making, and at the same time, enables generation of a composite safety index based on the rules in the inference system

1.3 Aim and Objectives

From the problem statement above, this study, therefore, aims to develop a comprehensive safety performance measurement framework for offshore oil and gas platforms which is subsequently validated against the actual safety performance of the platforms for its usability and reliability.

The following objectives, which constitute the basis of this study, are framed:

1. To identify the key indicators for measuring integrative safety performance of offshore oil and gas platforms in Malaysia.
2. To determine the weights of the key safety performance indicators via perceived importance of the indicators and perceived risk of failing to observe the indicators.
3. To determine the significant correlations between the safety factors.
4. To propose a framework of safety performance measurement using the key safety performance indicators and fuzzy inference system.
5. To validate the framework of safety performance measurement.

1.4 Scope of Research

The research is confined to the safety performance measurement of oil and gas platforms in Malaysia. The study is carried out in Malaysia, involving safety and health practitioners which are based in Malaysia. The selection and weights of indicators are associated with regional knowledge and experience. Framework validation is conducted with platforms operating in Malaysia. The research does not intend to establish industry-wide performance targets and standards for the indicators proposed due to the complexity of such endeavor considering different goals, plans and management approaches of different oil and gas companies.

1.5 Outline of Thesis

The following components of this thesis is structured in line with the conventional format in the Guidelines for the Preparation of Research Reports, Dissertations 2015 published by the University of Malaya. The components consist sequentially of:

1. Chapter one – introduction which includes important background of the study consisting of platforms' safety, safety performance measurement, safety indicators and fuzzy inference system. A problem statement detailing the problems in safety performance measurement of offshore oil and gas platforms and the need of this study to address the problems is also included. This chapter outlines the aim, objectives and the structure of this thesis.
2. Chapter two – literature review provides a detailed description of previous studies carried out in identification of health and safety indicators for offshore oil and gas operations, a historical overview and illustrations of the current practices of safety management, particularly safety performance evaluation on offshore oil and gas platforms as well as the development and adoption of fuzzy inference system for safety performance evaluation. The literature review highlights the gap in this area of research and how this study fills in the gap.
3. Chapter three – methodology presents justification and a detailed illustration of the methods used for data collection including the development, validation and administration of questionnaire as well as statistical techniques used in data analysis. Methodology also includes procedures in deriving the compliance scores for the respective safety factors, development of fuzzy inference system for safety performance evaluation and validation of the safety performance measurement framework using actual safety data from offshore oil platforms in Malaysia.

4. Chapter four – results showcases the findings of the study in the forms of tables, graphs and diagrams. Instances are tables showing descriptive statistics, dendrogram showing relationship between safety factors and graphs demonstrating how the crisp outputs of different input membership function scenarios and set-up of the fuzzy inference system vary with the safety scores of actual platforms as well as testing scenarios.
5. Chapter five – discussion covers critical accounts of the findings, particularly the perceived importance and perceived risk of the indicators, the relationship between perceived importance and perceived risk, the correlations between safety factors as well as the applicability and testing results of the fuzzy inference system. Discussion also highlights significance and contributions of the study to safety of offshore oil and gas sector.
6. Chapter six – conclusion provides a summary of the major findings, limitations of the study and suggestions for further study.

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

The literature review begins by providing a detailed illustration of how offshore safety has evolved globally and in Malaysia, leading to its current state predominated by two major domains, i.e. personal safety, and process safety, interchangeably known as asset integrity. The review then proceeds to provide background of the two safety domains and highlights a lack of effort to bring the two domains together in the current safety performance measurement practice which calls for a systemic approach to safety management. The review also points to the importance of indicators in safety performance measurement and provides an illustration of historical development of safety indicators. The review then details the adoption of personal and process safety indicators in the offshore oil and gas sector which sets the tone for the need to integrate the relevant leading and lagging indicators from multiple sources to yield a comprehensive safety performance measurement framework for offshore oil and gas installations. The review compares the frameworks of composite indicator development and proposes the potential integration of fuzzy inference system for safety index generation.

2.2 Historical Perspective of Safety in Offshore Operations

2.2.1 A Global Perspective

The beginning of oil exploration in Malaysia was marked by discovery of the first oil well by Shell on top of Canada Hill in Miri, Sarawak (Morshidi, 2009). Oil exploration then moved offshore after the onshore oil well closed down. Important milestones in the history of offshore exploration in Sarawak were the discovery of Baram offshore filed in 1963 and subsequently, other offshore fields including West Lutong, Tukau, Baronia, Betty, Bakau and Bokor. With advancement in drilling technology, offshore explosion moves progressively to deeper waters (Morshidi, 2009).

Due to remoteness of offshore oil and gas platforms, safety on the offshore platforms is of utmost importance. Inclement weathers on the sea frequently expose workers to external hazards in addition to the occupational hazards they face for instance noise, moving objects, falling objects, fire and ergonomic concerns (Dahl & Olen, 2013). Process hazards could potentially escalate into major industrial accidents such as explosions and fire, resulting in more concerns to the health and safety of workers on oil and gas platforms. In addition, emergency response and securing help during occurrence of accidents could be complicated by the geographical locations of the platform leading to serious consequences (Høivik et al., 2009).

Maintaining high-level safety in the oil and gas sector, particular for offshore operations has been given much attention globally. Safety in offshore operations has made tremendous progress over the years since the first free-standing oil drilling structure was erected in the Gulf of Mexico in 1938 about 1.5 miles from the shore (Pratt et al., 1997). These offshore structures were subsequently erected further from the coast and the first well that went out of sight from the land was a platform 12 miles offshore of Louisiana. The early phase of offshore operations was governed by very few legislations and were extremely hazardous due to technical constraints, adverse marine environment, high operational costs and the pressure to produce oil in the shortest possible time (Pratt et al., 1997; Veldman & Lagers, 1997).

In the 1950s and 1960s, oil exploration moved progressively further to deeper water and the use of mobile drilling units increased. The emergence of jack-up rigs made drilling in water deeper than 100 feet possible. However, safety concerns loomed due to uncertainty in the applicability of land-based technologies and practices in offshore environment. Unlike the platforms now, design and construction of early platforms had little consideration of workers' safety, with the decks cluttered with equipment, living area located near high-risk equipment and compressor rooms (Veldman & Lagers, 1997; Kletz, 1999). Manual handling of pipes and chemicals were a common practice while the pressure to produce persisted. In addition, offshore workers were also exposed to hazards associated with transportation of personnel, particularly the hazards of moving between boats and platforms using cargo baskets and swing ropes and potential helicopter accidents during adverse weather (Mannan et al., 2012).

Between 1955 and 1957, 13 fatalities were reported due to overturning of four drilling vessels and the cause was partly due to design flaws of the jack-ups causing instability and a lack of emphasis on safety. A lack of safety regulations resulted in subjective definitions of safety, hence serious inadequacy of safe practices and safety programs (Transportation Research Board US, 2016). Companies had reactive approach on safety and often took corrective measures after occurrence of fatal accidents. In general, safety during the period was minimal, be it regulations or practices (Transportation Research Board US, 2016).

Safety of offshore operations only started to receive attention in 1958. From 1958 to 1960, legislations were made in the United States to specify well drilling, plugging and abandonment procedures, to regulate well production rates as well as to mandate reporting of inspection results and corrective actions by facility inspectors (Transportation

Research Board US, 2016). However, enforcement of the legislations was deficient due to funding and manpower constraints. Reporting of data related to injuries, fatalities and accidents in oil and gas operations were inconsistent, leading to difficulty in statistical analyses and trend identification. Safety concerns and sharp rising accident rates in drilling vessels resulted in increment of global insurance rates on the vessels and incurrence of costs of uninsured exposures such as production loss on the operators (Transportation Research Board US, 2016).

The period between 1965 and 1990 was marked by improvement in the safety of offshore operations during which many design and technical constraints were resolved (Priest, 2008). During this period, union organizers had an important role to play in the initial improvement of safety standards and technologies via efforts to promote safety of divers. This effort catalyzed formation of new United States Coast Guard (USCG) regulations (Priest, 2008). In subsequent years, the oil and gas sector witnessed a number of major accidents. A blowout occurred in Santa Barbara Channel, California in 1969 resulting in spillage of 80000 barrels of oil catalyzed the passage of the National Environmental Policy Act (Priest, 2008). In 1970, a platform offshore of Louisiana experienced blowout and fire causing a spillage of 30000 barrels of oil though no fatalities were reported. In the same year, a production platform also offshore of Louisiana reported a blowout killing 4 men, injuring 37 and polluting the environment due to spillage (Pratt et al., 1997).

In the North Sea, the *Sea Gem* drilling vessel collapsed in 1965 causing 13 casualties. In 1980, a semisubmersible drilling rig called *Alexander Kiellend* in the North Sea capsized causing 123 casualties. In 1988, 167 fatalities were reported in the explosion and fire at the *Piper Alpha*. Primary causes of these major accidents were identified to be faulty material, process failure, human factors, defective safety management, a lack of safety culture, and design failure as in the case of *Sea Gem* (Burke, 2013) and *Alexander Kielland* accidents. A major contributing factor to human errors and defective safety management was the deficiency of safety regulations and enforcement (Arnold, 2015). In addition, process safety was not given adequate attention until late 1960s during which process safety practices such as installation of high-pressure sensors, shut-in valves and emergency shutdown system were introduced though reliability of the devise were not testified. Safety concerns of offshore operations were again brought to attention through a report of the Congressional Office of Technology Assessment on deepwater drilling, which highlighted the importance of prevention of occupational injuries and fatalities in deepwater operations and the need of safety plans integrating technical, organizational and human aspects of offshore operations (Transportation Research Board US, 2016). Endeavors to improve safety regulations took off in early 1970s with new regulations made for safety features on platforms and process safety as well as revision of operating procedures on platforms. At the same time, more collaboration between the industry and USCG were seen for instance the collaborative effort of American Petroleum Institute (API), Offshore Operators Committee and Anti-Pollution Equipment Committee in revision of regulations associated with offshore operations (Priest, 2008; Arnold, 2015).

During the same period, global attention on offshore safety heightened. Following *Piper Alpha*, an official public inquiry was chaired by Lord Cullen to investigate the causes of the disaster and recommend improvement to the safety of offshore operations (Hopkins, 2009). Lord Cullen's report was instrumental to the advancement of offshore safety in the United Kingdom. He made 106 recommendations pertaining to safety governance of offshore operations, including establishment of a regulatory unit in-charge of the health and safety of offshore oil and gas operations which catalyzed the formation of Health and Safety Executive's (HSE) Offshore Safety Division (NASA, 2013). Lord Cullen's report also played a crucial role in subsequent passing of the Offshore Installations (Safety Case) Regulations which came into force in 1992 and necessitates offshore operators to submit safety case to the HSE which comprises information on health and safety management in place and control of major hazards on offshore installations. Prior to Safety Case Regulations, the Offshore Installations (Safety Representatives and Safety Committees) Regulations already came into force in the UK in 1989 which mandates duty holders to consult employees in preparation of safety case (NASA, 2013).

In the 1990s, technologies and safety standards related to offshore oil and gas operations have achieved tremendous improvement and it was generally agreed that most major accidents were caused by human error instead of technical failure or non-compliance with industry safety standards. Human errors were traced to inadequate training and supervision, incomprehensive operating procedures and over-reliance on regulations, hence the emphasis in competence building, promoting safety culture and proactive approach to safety (Priest, 2008). It is worthwhile to look at how competence and safety culture contribute to the performance of other safety factors and overall safety performance in offshore operations.

2.2.2 Offshore Safety in Malaysia

Development of safety in the Malaysian offshore operations is closely tied to the global advancement in this area. While the concept of safety was still far-fetched during drilling of the first oil producing well named Grand Oil Lady in Miri, Sarawak, subsequent offshore explorations and operations in 1965 by Royal Dutch Shell introduced the technology and system in the Malaysian offshore sector. Safety of offshore operations then was still loosely defined but it served as the basis for subsequent development in this respect (Morshidi, 2009).

Until the end of the 1960s, Shell and Esso were the only players in upstream production, downstream oil refining and sales in Malaysia. After that, new players began to share the venture but they were almost entirely foreign companies. Therefore, policies and legislations governing the Malaysian oil and gas sector were formed leading to the formation of a national oil company called Petroliam National Berhad (PETRONAS) in 1974. In October the same year, the Petroleum Development Act was enacted. The Act promulgates a Production Sharing System (PSS) granting Malaysia full control of the petroleum resources within its territory, in contrast to the concession system prior to this where oil and gas companies holding the concessions assumed full authority over the resources therein (Abdullah & Basirun, 2013). Matter-of-factly, PETRONAS becomes the sole owner and manager of the oil and gas resources, and assumes control over downstream activities.

An important milestone in the safety of offshore operations in Malaysia is the enactment of the Petroleum (Safety Measures) Act in 1984 which regulates activities related to transportation, storage and utilization of petroleum. Two regulations were made under the Act, i.e. the Petroleum (Safety Measures) (Transportation of Petroleum by Pipelines) Regulations 1985 and Petroleum (Safety Measures) (Transportation of Petroleum by Water) (Abdullah & Basirun, 2013). Prior to enactment of the Act, the Factory and Machinery Act (FMA) already came into force in 1967 providing governance over safety, health and welfare of workers in factories as well as registration and inspection of machinery. The FMA identified a platform as a factory with well-defined boundary and machinery to perform various operations. Offshore oil and gas platforms are therefore subject to the FMA. Petroleum Mining Act was passed a year before the FMA but deals with matters related to application of exploration license or petroleum agreement, hence limited implications on safety of offshore operations (Mohamad Razali, 2005).

Due to shortcomings of the FMA which was prescriptive with limited scope of application, it was superseded by Occupational Safety and Health Act 1994. The Act comes into force to promote and maintain safety and health at work including offshore installations. It mandates establishment of safety committee, employment of safety officers, conducting of chemical health risk assessment at facilities with industrial major accidents hazards, industrial hygiene monitoring and medical surveillance of workers, among other safety measures (Abdullah & Basirun, 2013).

Tracing the history of offshore operations in Malaysia, there were very few mentions of major offshore accidents. The recent mentions of oil and gas related incidents were an oil tanker burst into fire and exploded at the Jetty of Petronas Chemicals Methanol Sdn Bhd in July 2012 while loading methanol, and two workers succumbed while the safety boat they were doing inspection on fell into the sea. However, the first incident is not platform-related and the second is not categorized as a major accidents (Abdullah & Basirun, 2013). While the reporting culture of safety incidents particularly industrial and oil and gas related ones is in the course of further improvement, the oil and gas safety practices in Malaysia have evolved in tandem with the global practices. This is partly due to involvement of international oil and gas companies in the oil and gas development of Malaysia since the early days (Mohamad Razali, 2005).

2.3 Development of Offshore Oil and Gas Safety

Safety of the Malaysian offshore sector has developed in tandem with the global practices and with the emergence of safety legislations in the country. On a global scale, the development of process safety is often tied to industrial disasters. Flixborough explosion in the United Kingdom in 1974 led to the formation of the Advisory Committee on Major Hazards and subsequently efforts and legislations related to control of major industrial accidents worldwide. Incident report of Flixborough explosion recommended consequence modelling and risk assessment to be carried out for industrial facilities posing major accident hazards (Kletz, 1999; Bhandari & Azevedo, 2013).

In 1976, leakage of dioxins from a chemical manufacturing plant north of Milan, Italy exposed a large number of residents to the chemical (Zuijderduijn, 1999). The incident brought further attention to industrial safety and led to the passing of Seveso Directive in Europe in 1984 to prevent and control industrial accidents. The directive has later been integrated into EU's Safety of Offshore Oil and Gas Operations Directive. A year later in the US, the Centre for Chemical Process Safety (CCPS) was established under AlChE. The Alpha Piper accident in 1988 led to tightening of offshore safety in the UK and the Macondo blowout in the Gulf of Mexico in April 2010 resulted in implementation of Drilling Safety Rule as well as modification of Workplace Safety Rule in the US the same year (Kletz, 1999; CSB, 2012).

With the quest to improve industrial process and occupational safety, tools and techniques have been progressively developed. Before 1970s, tools such as What-If analysis, checklist, hazard and operability study (HAZOP), fault tree and event tree analyses were already available to aid identification of hazards, assessment of risks and consequences. HAZOP was in fact developed in 1963 by ICI but only came into the limelight in the mid-70s post-Flixborough and Seveso. Management of change (MOC) which is a common practice in offshore operations was emphasized after the Flixborough disaster. Fault tree analysis created in the early 1960s has achieved advancement over the years in methodology and amalgamation with computer (Mannan et al., 2012).

The following decade saw refinement of fire and explosion models as well as mechanisms of chemical releases and evaporation. Quantitative risk assessment (QRA) of offshore facilities gained popularity after *Piper Alpha* and *Alexander Kielland*. The concept of safety culture was introduced after the Chernobyl accident in April 1986 causing the atmospheric release and spread of large quantities of radioactive particles over large area. The immediate cause was mistakes in a routine maintenance procedure and the root causes were traced to design flaws and human error. This led to increased attention on safety management system, for instance MOC and organizational culture (Mannan et al., 2012; Mannan, 2014).

The 1990s was marked by emergence of new legislations, the collection of safety statistics, establishment of safety databases and reporting of safety performance. While legislations and major industrial accidents set the path of safety advances in offshore operations, the safety approaches used evolve. The concept of safety barriers widely adopted in the oil and gas sector has its origin in Reason's "Swiss-cheese" (Reason, 1997) wherein the barriers represent layers of defence to major incidents. The barriers can be classified as "hard" barriers consisting of engineering control and incorporation of safety into engineering designs, and "soft" barriers consisting of administrative and procedural control. The barriers-based system has since evolved and each barrier now consists of sub-barriers called safety critical elements (SCE) in offshore technical integrity management (HSE, 2008).

SCE according to the Offshore Installations (Safety Case) Regulations 2005 of the UK is defined as parts of an installation or plant which play crucial role in prevention or minimization of impacts of major accidents (HSE, 2006). Failure of SCE could therefore escalate into occurrence of major accidents. The SCEs and performance standards identified via hazard and effects management process forms the first step of technical integrity management, followed by establishment of maintenance, inspection and testing plan of the SCEs. Examples of SCEs in the process containment barrier are pressure vessel, heat exchangers, rotating equipping, piping, etc. (Frens & Berg, 2014). It is becoming obvious that system approach prevails in the offshore safety with safety being 'managed', hence an integral part of management system (Oedewald, 2014).

Prior to barrier-based safety management system, the loss prevention approach was already developed by the Institute of Chemical Engineers, UK in the 1960. The loss prevention approach marks the beginning of proactive approach to safety via identification of hazards and control of risks before occurrence of accident (Kletz, 1999). The approach emphasizes systematic safety management in contrast to trial and error method prior to late 1960s during which technical safety consisted essentially of reactions to reduce problems arising from new techniques adopted in the industry. Loss prevention approach has widened safety beyond technology-related concerns and placed focus on accidents and near-misses. The approach gained popularity in the oil and chemical industries and is often also known as process safety (Pratt et al., 1997; Kletz, 1999).

The effectiveness of loss prevention lies at the systematic prioritization of safety actions. In order to achieve this, hazard analysis is frequently used where risks above acceptable level are prioritized for mitigations. Hazard analysis was initially applied in occupational safety to safeguard employees' wellbeing. Techniques of hazard analysis progressively develop and mature (US EPA, 2008; Mannan, 2014) with emergence of HAZOP in 1963 and subsequently quantitative risk assessment (QRA) (Lawley, 1974). A quintessential aspect of loss prevention is inherently safer design (Umar, 2010). The first publication on inherently safer design came in 1978. However, it only received due attention after the release of intermediates from Union Carbide's pesticide plant in Bhopal killing more than 2000 people. The disaster raised questions on the need to store intermediates, hence reduction in storage of intermediates. Inherently safer design is at the core of loss prevention as it targets at avoidance of hazards at the design stage, hence eliminates the need to deal with the hazards later (Kletz, 1999; Mannan, 2014). The concept of loss prevention also catalysed studies on prevention and consequences of leaks, explosions (Brasie & Simpson, 1968) and vapour clouds (Strehlow, 1973; McQuaid, 1985), as well as testing of processes with instrumentation.

Loss prevention sets the path for systematic approach in offshore safety. The systematic approach consists of inspection and maintenance plan, controlled plant modifications, operating procedures as well as human and organization factors which are in the limelight now (Mearns et al., 2010; Oedewald, 2014). The systematic approach in offshore operation's safety has gradually evolved into systemic approach with safety viewed as an interplay between human, organizational and technology factors. In systemic approach, safety culture came into the picture alongside process, equipment and occupational safety (Mearns, 2003; Oedewald, 2014). It can also be viewed as an amalgamation between process and occupational safety wherein focus is not only on technical and operation safety to prevent major industrial accidents but also on individual safety in discharge of duty. In addition to that, systemic approach shifts safety from compliance-driven to culture-driven, hence the emphasis of safety culture (Guldenmund, 2000; Leveson, 2015).

2.4 Current Safety Practices on Offshore Oil and Gas Platforms

The past five decades saw tremendous progress made in offshore operations' safety from reactive approach and legislation driven to proactive approach and culture driven via systemic view of safety (ILO, 2001). Today, oil and gas companies claim safety as their priority. Safety is subject to scrutiny be it for onshore or offshore operations. In line with the general principle of management, safety is also subject to continuous improvement.

2.4.1 Asset Integrity and Process Safety Management

In the offshore sector, asset integrity management is at the centre of safety management and has overlapping features with process safety. Asset integrity management encompasses the management of people, systems, processes and resources to ensure assets operate with minimal risks to employees, the public and the environment (Hassan & Khan, 2012). There are three main aspects of asset integrity management, i.e. structural, technical and operating integrity (Lauder, 2012; Frens & Berg, 2014).

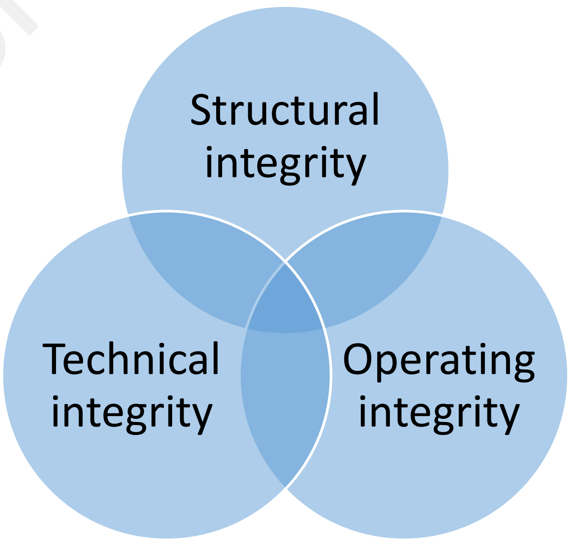


Figure 2.1: Elements of Asset Integrity Management (Frens & Berg, 2014)

Asset integrity management of offshore operations began to receive attention after the Piper Alpha accident in 1988, which prompted oil and gas operators to review their strategies in assessing and managing integrity of their installations. Asset integrity management post-Piper Alpha was adopted in response to the increasing pressure to ensure safety of oil platforms due to emergence of more stringent safety legislations (Oil and Gas UK, 2008; NASA, 2013). Among the measures taken to enhance asset integrity were improving permit-to-work system, relocation of pipeline emergency shutdown valves and installation of isolation devices (Lauder, 2012). Asset integrity and process safety are similar in many respects. It adopts multiple safety approaches such as barrier-based system, safer designs and reliability engineering. Asset integrity management spans the entire life-cycle of a platform. Process safety can be understood as the operational aspect of asset integrity, though in practice, asset integrity is often oriented towards the hard barriers of a system comprising for instance structures, piping and instrumentation, and equipment (Ratnayake, 2012; Hassan & Abu Husain, 2013).

Therefore, taking into account the subtle distinction in the practical aspect of asset integrity and process safety, safety on offshore oil and gas platforms can be classified into two major domains i.e. personal safety and asset integrity, equivalent to or encompassing process safety. Asset integrity and process safety management starts from the development phase of an offshore project, commencing with evaluation and review of development options and initial operations assessment. Once the development option is finalized, the concept is formulated and evaluated. Initial analysis of hazard and effect management process (HEMP) is conducted for each concept option and the proposed concept is reviewed to ensure the 'ALARP' approach has been practiced whereby risks identified are reduced to as low as reasonably practicable (Frens & Berg, 2014).

Front end engineering design (FEED) commences upon finalization of the project concept. Another HEMP analysis is carried out for FEED. Techniques for HEMP analysis vary. The most commonly used HEMP technique is called the Bowtie method, deriving its name from the diagram showing the cause and effect relationships of risks identified which looks like a bowtie (**Figure 2.2**) (Zuijderduijn, 1999). The Bowtie method not only identifies potential accidents arising from a hazard, it also identifies control measures for the scenarios and the ways the control measures could fail. It provides a means to 'ALARP' in risk management (Jager, 2013). The Bowtie diagram was said to have made its debut at the University of Queensland, Australia in 1979 but its origin and development remains unverified (CGE Risk Management Solutions, 2017). The method was first adopted by the Royal Dutch Shell and is now widely used by industries and regulators. The Bowtie forms part of risk-based approach in safety management which involves risk assessment to better define the magnitude of an industrial occurrence, the frequency of occurrence and the effectiveness of barriers to control the risks (Frens & Berg, 2014).

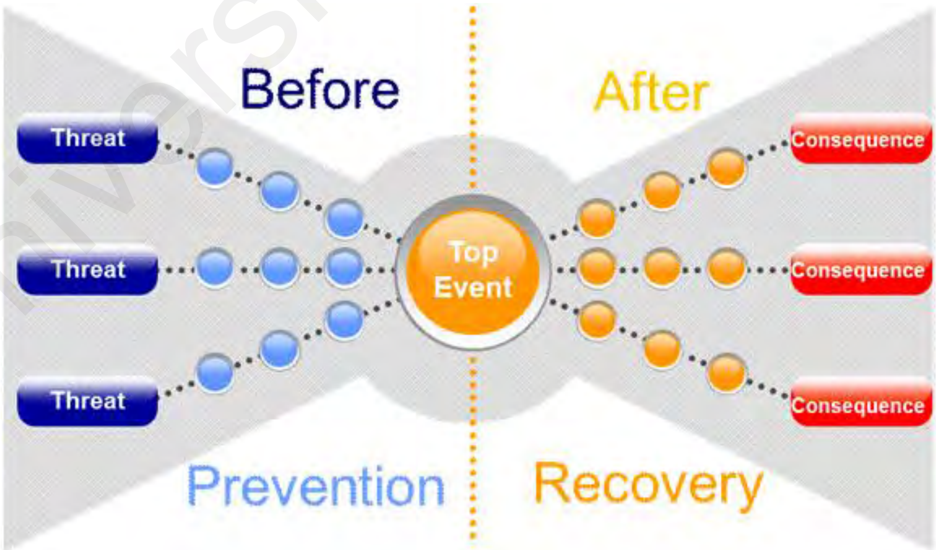


Figure 2.2: Bowtie Diagram (GRE Risk Management Solutions, 2017)

Determination of groups of safety critical elements (SCEs) follows the HEMP in design stage, and subsequently, operation envelope as well as performance standards are defined (Frens & Berg, 2014). Design safety case is often formulated at this stage as required by the legislations in the UK and Australia. In 2016, Brunei adds to the list of countries requiring safety case for offshore installations prior to operations (Thien, 2016).

In execution phase, the detailed facilities design is already in place. Refined HEMP analyses with specific bowties are conducted. SCEs identified are entered into asset register and loaded into computerized maintenance management system (Petronas, 2014). The design performance standards and assurance measures are refined, and the operational phase performance standards and assurance measures are established. Operations safety case is formulated as in the case of design safety case (Frens & Berg, 2014). Facilities are then constructed and the operational readiness and assurance plan is executed. Commissioning and handover of facilities to operators mark the end of this stage (Ramasamy & Yusof, 2015).

During operation, the SCE performance assurance tasks and measures are managed, with deviations controlled. Reporting of SCE status and key performance index as well as management of change also take place during this stage (Frens & Berg, 2014; Petronas, 2014). With increasing emphasis placed on human and organizational factors in safety management, measures to reduce fatigue, increase alertness, assure competence as well as to increase safety culture and behaviour are incorporated into lifecycle of offshore installations starting from FEED to decommissioning (Flin, 2000; Jensen, 2014). An overview of asset integrity management of offshore platform is shown in **Figure 2.3**.

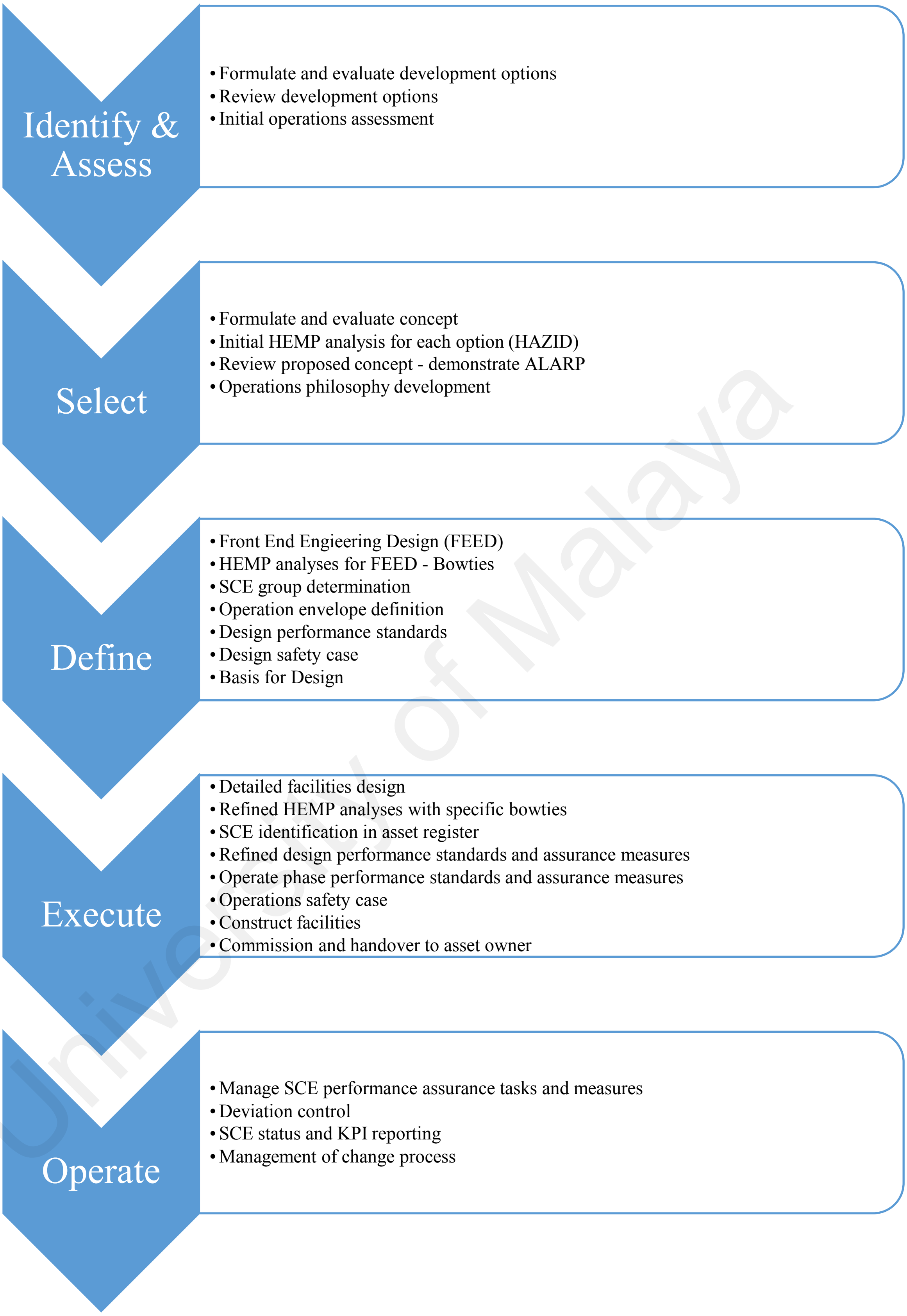


Figure 2.3: Overview of Asset Integrity Management of Offshore Platform

Zooming in to specific domains of asset integrity management, technical integrity management involves identifying SCEs and performance standards using HEMP, establishing and executing maintenance, inspection and test plan, as well as monitoring the SCE functions and taking corrective actions where necessary (Frens & Berg, 2014). Different oil and gas companies may have different approaches in monitoring the SCE functions. One of the methods is facility status reporting. Between 2004 and 2007, the HSE (2008) initiated the Asset Integrity Key Program, focusing on maintenance management of safety critical elements (SCEs) of offshore installations comprising fixed installations, floating production, floating production storage and offloading vessels and mobile drilling rigs. Participating oil and gas companies align their facility status reporting to the recommendations of the HSE, incorporating the suggested elements and the traffic light system to indicate compliance status of the SCEs where red indicates non-compliance, amber indicates isolated failure and green indicates compliance (HSE, 2009). However, facility status reporting does not incorporate sufficient leading indicators which capture the preventive effort made in managing major hazards and does not place sufficient emphasis on safety culture and human factors (HSE, 2009).

Operating integrity engages active identification and management of vulnerabilities, risk assessment, risk control, control measure implementation as well as review by senior leadership. Operating integrity ensures processes are within operating and pressure/ temperature envelop. It involves constant review of operating performance at various levels and management of alarm, for instance via alarm steering committee, alarms database to capture alarm purpose, and automatic suppression to eliminate false alarms (Jager, 2013).

Structural integrity focuses on ensuring offshore installations are able to support a designed load without failing and incorporation of past failures into future designs. Early development of structural integrity management was associated with aging of offshore installations, failure to follow good practice and shortcomings in guidance documents. To date, the structural integrity management framework is provided by API and ISO (Pushkar et al., 2006; Potty & Mohd. Akram, 2009; Ramasamy & Yusof, 2015). As structural integrity is multi-disciplinary and highly technical involving mechanical, civil and structural aspects, it is beyond the scope of process safety performance measurement proposed in this study.

2.4.2 Personal Safety Management

Personal safety comprises another major domains of offshore safety management. Personal safety centres on ensuring the health, safety and wellbeing of individual workers in the workplace by reducing, hence minimizing their exposure to occupational risks as low as reasonably practicable (ILO, 2001).

In the offshore context, personal safety focuses on reducing workers' exposure to radiations, chemicals, noise, vibration, extreme temperatures and ergonomic hazards via measures consisting of industrial hygiene monitoring, chemical health risk assessment, job safety analysis, medical surveillance, safety awareness program and work arrangement to reduce fatigue and increase alertness, to name a few (Venkataraman, 2008). In Malaysia, industrial hygiene monitoring and chemical health risk assessment are regulated by the Occupational Safety and Health (Use and Standards of Exposure of Chemicals Hazardous to Health) Regulations 2000, to ensure adequate protection of workers likely to be exposed to hazardous chemicals at workplace via reliable risk assessment to characterize the exposure and regular monitoring to gauge the actual levels of chemicals at the workplace, hence the exposure of workers to the chemicals. Industrial hygiene monitoring not only captures actual chemical exposures, but provides information for selection, determination of effectiveness, and maintenance of control measures.

Personal safety includes hearing conservation of offshore platforms' workers via audiometric testing and noise exposure monitoring to reduce the risks of hearing impairment (Petronas, 2013). HSE (2014) reported that 30% of workers on oil and gas platforms are exposed to noise level higher than 85dB(A), while health-related matters such as food hygiene and infection outbreaks remain a risk on the platforms. This affirms the need to integrate personal safety as part of safety performance measurement in the offshore oil and gas sector which is currently not captured in performance measurement. In addition, fatigue management has been promulgated by OGP-IPIECA (2012) and Petronas (2013) as an important aspect of occupational health performance. Fatigue has been associated with work arrangement, particularly extended shift pattern, leading potentially to impaired cognitive function and responses. Fatigue of oil and gas workers may have implications on alertness, leading to human errors in process safety management.

Personal safety also deals with the human factors encompassing competence building, taking the correct procedures and use of personal protective equipment (Rundmo, 1994; ISO,2016). It often focuses on reducing unsafe acts through safety awareness programs which form part of behavioural-based safety involving influencing the behaviours of platforms' workers, thus, increasing the demonstration of pro-safety behaviours (Arezes & Miguel, 2008). As mentioned, personal safety endeavours to reduce risks causing personal harms such as slip and trip, falling from height, electrical exposure, struck-by, caught between and burns (IOGP, 2015).

Like process safety, it ultimately aims to decrease fatality, injury rates and near-misses. In addition, personal safety also looks into cases of occupational diseases and poisoning. It merges with process safety at the organizational level, with organizational culture as driving force of occupational and process safety (Guldenmund, 2000; Morrow et al., 2014). To support the claim, Olsen et al. (2015) revealed that work climate factors are negatively correlated with incidences of hydrocarbon leak and can be used to predict leaks of different severity. Bergh et al. (2014) also reported positive correlation between psychological risk scores and incidences of hydrocarbon leaks. Safety climate accounts for approximately 20% of hydrocarbon leaks severity and thus further depicting the importance of organizational factors on process safety.

Despite the importance of personal safety, the related literature tended to addressed the personal safety aspects separately, for instance work climate by Olsen et al. (2015), psychological risk by Bergh et al., (2014), competence-building and use of PPE by Arezes & Miguel (2008), without attempting to unify the major aspects of personal safety with existing guidelines and legislative requirements to yield a comprehensive list of personal safety indicators for performance evaluation.

2.5 Safety Performance Measurement

It is apparent at this point that safety is an interplay between technical, organizational and human factors, managed via asset integrity or process safety and personal safety. This systemic approach to safety, having evolved from the early reactive, compliance driven approaches and the recent systematic approach, relies on integrative management system.

The systemic approach can be linked to the concept of safety system or safety system engineering popularized in the 1970s by the works of Bertalanffy (1971), Johnson (1980), Hammer (1989), etc. Safety system incorporated safety management techniques into system engineering, for instance product safety was integrated into the design of production processes. In the late 1970s, focus of safety management was placed on technical personnel such as control room operators and maintenance works in addition to technical aspects due to occurrence of major accidents related to human errors. For instance, the Three Mile Island accident in March 1979 resulting in core meltdown of a nuclear plant and environmental release of radioactive material was due to failure of control room operators to detect loss of coolant partly attributed to design of control room (Johnson, 1980). Subsequent incident reports pointed out that human element was overshadowed by emphasis on safety of equipment and there was shortcomings of the "system" governing operations, communication among key players and organizational factors (Johnson, 1980; Hammer, 1989).

By mid-1980s, systematic safety management and safety culture became a popular subject, much attributed to the Chernobyl accident in 1986 which was the culmination of numerous safety downfalls including ambiguous operating procedures, flawed designs and safety features, breaching of safety rules by operating staff, lack of competence and pressures to meet production goals (Hammer, 1989). This, again, highlighted that accidents were caused not only by technical failure but human errors and organizational factors. Ensuing incident report pointed to a lack of safety culture, thus, bringing safety culture to attention. However, safety culture does not provide systemic approach to safety because it is perceived as another source of failure among technical and individual factors and it focuses too much on individual behaviours (Rentch, 1990; Witt et al., 1994). A more holistic view of safety management is necessary with safety being an emergent property that is subject to continuous improvement throughout the life of an installation. This gave rise to sociotechnical and later systemic approach to safety (Oedewald, 2014).

Now, safety management is defined as "the management process to ensure that risks are reduced to a level as low as reasonably practicable via hazard identification, risk assessment, control and monitoring" (Gupta & Edwards, 2002). It is characterized by a business-like approach to safety and includes typical elements of a management system comprising policy setting, planning, organization, performance measurement, evaluation and continuous improvement. Popular models of safety management are provided by International Labour Organization (2001) in ILO-OSH 2001 Guidelines in Occupational Safety and Health Management Systems and OHSAS 18001 developed collaboratively by multiple national and international standard and certification agencies. OHSAS 18001 incorporates the safety management traits of several national standards for instance BS8800: 1996 Guide to occupational health and safety management systems, and Draft AS/NZ 4801 Occupational health and safety management systems – Specification with guidance for use.

The above models of safety management are mainly related to personal safety. Guidelines related to process safety management that have been published by agencies such as API, CCPS, IOGP and HSE point to the importance of performance measurement to provide early warnings of system deviations, hence timely corrective actions. It is obvious that safety performance measurement forms an integral part of the safety management system, be it occupational or process safety (HSE, 2006; API, 2010; CCPS, 2011; OGP, 2011). In ILO-OSH 2001, the continual improvement cycle of safety management consists of policy, organizing, planning & implementation, evaluation and action for improvement. Performance monitoring and measurement is an element of evaluation during which safety performance is continuously and systematically monitored, measured and recorded, responsibilities for various levels of monitoring is defined and the procedures of performance monitoring and measurement is consistently reviewed (ILO, 2011).

Performance indicators have a central role in safety performance measurement. In the oil and gas sector, performance measurement is conducted both for asset integrity and occupational safety at facility and corporate level (Øien et al., 2010; Øien et al., 2011). Facility-level asset integrity performance measurement is characterized by categories of indicators ranging from structural integrity, process containment to emergency response (Frens & Berg, 2014). Compliance status of the indicator categories is shown using a traffic light system promulgated by the HSE in its asset integrity program. The compliance status of performance indicators is determined by comparing the actual performance against the performance standards and targets set. (HSE, 2008). Weights can be assigned to indicators under a particular safety category for instance maintenance measure, where the indicators may comprise preventive maintenance compliance, corrective maintenance compliance, corrective maintenance workload, etc., depending to the practice opted (Jager, 2013). Weights usually represent the importance of an indicator and appear in scoring system to generate a score for an indicator or a safety category. However, the adoption of weights for safety indicators is not a standard practice and there are companies which do not attach weights to the indicators used, thus, assuming the indicators have equivalent importance (Walker & Cheyne, 2005). Where weights are used, it is often based on management's judgement with limited attempts to garner consensus, be it organization-wide or industry-wide (Vinnem, 1998).

Personal safety performance is usually measured using indicators such as number of fatalities, fatal accident, incident rates, total recordable injury rate and lost time injury frequency. As process safety performance also uses these indicators, the distinction is often drawn by breaking down the fatality and injury rates based on categories and causes (IOGP, 2015; NOPSEMA, 2015; IOGP, 2016). Fatality is defined as death, either immediate or within one year of the date of injury, of an employee or a contractor's employee due to work, while fatal accidents are accidents resulting in fatality. Total recordable incidents encompass all fatalities, lost time injuries, illnesses and medical treatment cases occurring at work but do not include first-aid injury. Lost time injury results in inability of an employee to continue work, hence a loss of productive work time. Near-misses, on the other hand, are unintended occurrences that could potentially harm human, the environment, and properties (Petronas, 2015; IOGP, 2016). Incident and injury rates are counted as occurrences per million man-hours worked. In the case of total recordable incident rate for instance, it is counted as number of total recordable cases per million man-hours worked (HSE, 2015; Petronas, 2015; IOGP, 2016).

Of late, occupational diseases such as musculoskeletal disorders have been included in measurement of personal safety performance. In performance measurement, it is typical to set performance standards or objectives against which performance is measured. The measurement system can be active or reactive. Active systems look into the extents to which objectives and compliance with standards are achieved while reactive systems monitor the occurrence of accidents, incidents and near-misses to determine the root causes, system's weakness, and other corrective actions (HSE, 2006). Indicators used for active and reactive performance measurement are different. The former consists primarily of leading indicators while the later consists primarily of lagging indicators. Though the offshore sector adopts both types of performance measurement, the leading indicators do not receive similar attention as the lagging indicators. This is also reflected in corporate reports of safety performance where lagging indicators predominate. It is also common that process and personal safety performance measurements are treated as separate domains in the offshore sector with minimal effort to integrate both in spite of the promulgation of 'systemic' safety management approach.

2.6 Historical Perspective of Safety Performance Indicators

Lagging indicators measure number of incidents, injuries and damages beyond a certain level of seriousness. Leading indicators, on the other hand, provide indications of deviation from the ideal situation by assessing inputs to safety (CCPS, 2011) and are typified by indicators measuring mechanical integrity, action items follow-ups as well as training and competence (Reiman & Pietikainen, 2012).

Changes in a system are usually gradual and would only manifest over a long time. Such changes may not be observable on a day-to-day basis. Indicators enable data to be collected over time and trends to be identified (Vinnem, 1998). This facilitates continuous evaluation of a safety management system and allows timely corrective actions (HSE, 2006). Therefore, selection of indicators is crucial to optimize their roles in safety performance measurement. Hopkins (2009) once warned against the use of rate in safety measurement as it is only useful if the undesirable events measured occur frequent enough to constitute a rate.

Development of safety indicators has progressed in tandem with safety management approaches, from fatalities and injuries rates for reactive approach in the early years of safety development to the leading indicators gauging compliance with legislations and efforts taken for compliance driven and proactive approach in recent safety management.

As the types of indicators evolve with the approaches to safety, specific indicators emerge with the development of safety techniques. For instance, barriers-based system and loss prevention in process safety contributed to the ‘loss-of-containment’ as a process safety indicator (Øien et al., 2011; Leveson, 2015).

Safety performance measurement received much attention in the 1980s due to increasing focus on systematic approach to safety management and safety culture. However, the use of the term ‘indicator’ is relatively new and early development of safety indicators was associated with safety monitoring of nuclear plants (Mearns, 2009) which became a concern after the occurrence of major accidents in the nuclear industry, particular the Three Mile Island and the Chernobyl.

The safety indicators development can be summarized in the following sequence:

1. Work initiated by the United States’ Nuclear Regulatory Commission (NRC)
2. Performance indicators by World Association of Nuclear Operators (WANO)
3. Operational safety indicators
4. Safety performance indicators
5. Operator specific safety indicators
6. Probabilistic indicators
7. PSA based risk indicators
8. Accident sequence precursors
9. The resilience engineering perspective on indicators

2.6.1 Work initiated by the United States' Nuclear Regulatory Commission (NRC)

A lack of empirical organizational analyses in the nuclear industry in the 1980s was the major driving force for initiation of a study called "Initial Empirical Analysis of Nuclear Power Plant Organisation and Its Effect on Safety Performance" which highlighted the importance of organizational structure such as work arrangement and assignment as indication of a nuclear plant's safety performance. The study subsequently yielded and validated a list of performance indicators for evaluation of organizational factors (Olson et al., 1985) and organizational effectiveness adopted by the NRC (Marcus et al., 1990). The organizational effectiveness indicators were later refined into two lines of management indicators for evaluation of resources utility, and assessment of delayed recognition and correction of problems respectively.

Concurrently, the NRC initiated projects to develop more responsive probabilistically-oriented indicators for measurement of system performance. One of the projects was led by Wreathall et al. (1990) to identify specific programmatic performance indicators related to nuclear plant maintenance. These initiatives marked the early attempts to develop risk-based indicator and set the path for development of probabilistic safety assessment (PSA) especially when there was increasing interest in deriving the probability of component failures instead of the actual systemic performance in the nuclear industry.

In 1991, Haber et al. steered the development of Nuclear Organisation and Management Analysis Concept (NOMAC). NOMAC formed the basis of the Work Process Analysis Model (WPAM) developed subsequently. The WPAM is an integrative model that applies qualitative and quantitative methods in assessing organisational dependencies between parameters such as hardware failures, human errors and common cause failures (Øien et al., 2010). In 1992, Wreathall et al. proposed a new framework called Integrated Safety Model (ISM) which brought together all performance indicators used by the NRC and gauged their relevance. The NRC promulgated integration of socio-organizational factors to risk assessment and technical evaluation of systems and had channelled much effort in investigating the influence of organizational factors to safety before shifting its focus to the development of risk based performance indicators (RBPIs).

2.6.2 WANO Performance Indicators

The World Association of Nuclear Operators (WANO) formed by the international nuclear power community in 1986 initiated effort to standardize performance indicators of nuclear power plant as well as to develop and implement detailed and specific plant indicators. The WANO indicators consisted initially of a series of direct or lagging indicators. Indirect or predictive indicators were later included due to increasing attention on the leading aspect of safety performance measurement (Øien et al., 2011).

2.6.3 Operational Safety Indicators

The IAEA (1999) presented a framework for identification of safety and economic performance indicators using a hierarchical structure with the operational safety of nuclear power plant at the top of the hierarchy, followed by operational safety attributes. Below the operational safety attributes were seven paramount safety indicators. The next levels were marked by 14 strategic indicators and 38 specific indicators respectively. This initiative formed a milestone in development of plant-specific indicators and paved the way to tier approach of indicator development as promulgated by the API and CCPS now. The early tier approach yielded two levels of indicators i.e. the paramount indicators also known as the high level indicators (HLI) and the specific indicators also known as the low level indicators (LLI).

Similar to the modern tier system, the paramount indicators consisted mainly of corporate-level indicators for decision making while the specific indicators focused on technical and operational levels to facilitate collection of specific information. These operational safety indicators were predecessors of the modern day process safety indicators (IAEA, 1999).

2.6.4 Safety Performance Indicators

In Scandinavia, a safety indicator project was launched to re-investigate the usefulness of WANO and other plant specific indicators in safety performance measurement (Holmberg et al., 1994; Øien et al., 2011). The project developed a framework based on risk assessment and the barrier-based system adopted in defence-in-depth strategy as shown in **Figure 2.4**. The framework identified four performance areas i.e. i.e. safety management forming level 1 safety barrier, control of operation forming level 2 safety barrier, safety functions forming level 3 safety barrier) as well as the physical barriers representing the hardware barriers. Under the framework, the performance areas were measured using direct indicators monitoring the equipment and hardware integrity, and indirect indicators monitoring the organizational/ administrative factors (Øien et al., 2011).

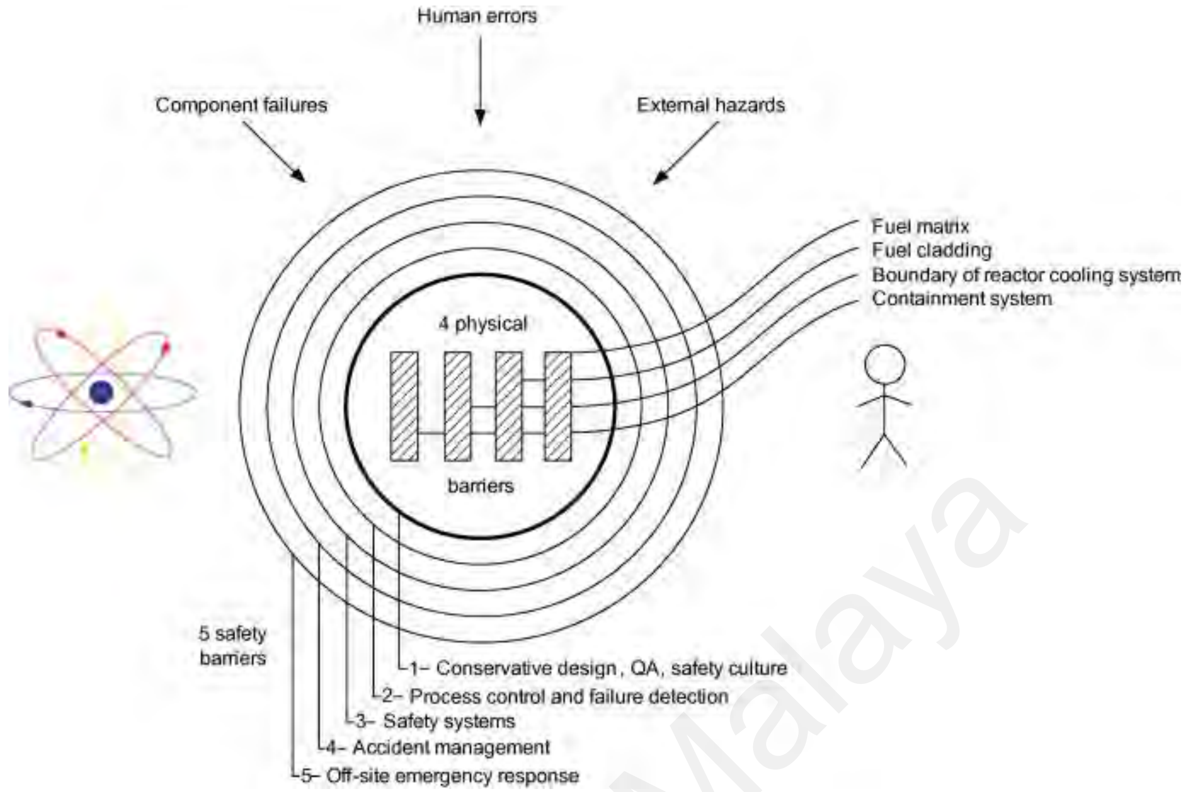


Figure 2.4: Illustration of the Defence-in-depth Strategy (Øien et al., 2011, p.154)

The project generated approximately 100 safety indicators sorted according to their name, function, purpose, definition, need for data, use and results.

2.6.5 Operator Specific Safety Indicators

Operator specific safety indicators resulted from the joint effort of Vattenfall and Nordic project (Holmberg et al., 1994) which yielded nine indicators, six of which were related to communication between the operator's central management and the individual power plant units. These indicators were helpful in identification of hidden safety issues.

2.6.6 Probabilistic Indicators

The Swedish Nuclear Power Inspectorate (SKI) established the STAGBAS II database which gathered statistical data of incidents from various safety function, systems and components (Øien et al., 2010). Trends from the statistical data facilitated identification of potential indicators. Relevance of each potential indicator, for instance isolation valve, was evaluated with plant specific risk analysis, to derive their importance in relation to the total risk. Scenarios causing failure of the indicators were later identified to determine underlying safety problems, thus, facilitating development of unit-specific probabilistic safety indicators which measure deviations in a system (Holmberg et al., 1994).

2.6.7 PSA-based Risk Indicators

Probabilistic Safety Assessment (PSA) involves systematic quantification of risk and enables safety issues to be identified (IAEA, 1999). This permits indicators monitoring the safety issues to be developed. PSA-based risk indicators were sorted based on levels as in a barrier-based system, i.e. level 1 indicators dealing with risks at facility-level for instance the frequency of core damage, as well as level 2 indicators encompassing, among others, probability of undesirable events, the deficiency of power plant in managing incidents hence preventing core damage, and the plant's deficiency in accidents management. Level 2 indicators were then divided into sub-categories, e.g. the primary indicators and the system unavailability indicators (Marcus et al., 1990).

PSA-based indicators are commonly used in long-term and short-term monitoring wherein long-term monitoring keeps plant risks in check over a period of time and short-term monitoring focuses on instantaneous risks. PSA-based indicators are also useful for retrospective and predictive monitoring with retrospective monitoring highlighting the major downfalls or achievements in a workplace over a past duration of interest and predictive monitoring emphasizing on minimization of planned risk by linking PSA to planning and change management (Øien & Sklet, 1999; Øien et al., 2011).

PSA was initially developed for the nuclear power industry but was later introduced to the oil and gas sector via the "Risk Indicator Project" jointly undertaken by Statoil and the Norwegian Petroleum Directorate which brought forth an improvised version of PSA called QRA (Øien & Sklet, 1999).

2.6.8 Accident Sequence Precursors

Accident Sequence Precursors (ASPs) are comparable to 'near misses'. An ASP can be an initiating event, a combination of initiating event with system failure and unavailability, as well as the occurrence of system failure and/ or unavailability for a given duration. Assessment of an ASP involves qualitative and quantitative analysis of a near miss or initiating event using risk analysis, i.e. PSA or QRA. Attempts had been made to integrate ASP and risk indicators to estimate events or ASPs at lower levels and enable early indication of negative trends (Johnsen & Rasmuson, 1996).

2.6.9 The Resilience Engineering Perspective on Indicators

Resilience is defined as the readiness to identify and manage changes and unexpected events (Woods, 2006). Resilience based indicators are especially useful when knowledge about a situation is lacking. These indicators consist of leading indicators which provide early warning and monitor organisational aspects and human performance such as management commitment, awareness, preparedness, flexibility and safety culture (Øien et al., 2010). According to Woods (2006), resilience is a collective trait contributed by factors such as buffering capacity, tolerance and cross-scale interactions. Nonetheless, a drawback of the resilience-based indicators is that they are fragmented due to a lack of socio-technical systemic approach to integrate human, organizational and technological factors in development of the indicators.

2.7 Development of Safety Indicators in the Oil and Gas Sector

In the oil and gas sector, development of safety indicators is often linked to the occurrence of major accidents. The Frigg Safety Case in 1995 led to the development of a series of safety indicators based on HSE regulations, sensitivity analyses via quantitative risk assessment (QRA) and subjective evaluations of critical safety factors (Vinnem, 1998). The indicators were technical-oriented and covered aspects such as leak frequency, hot work control, automatic gas and fire detection, etc.

With introduction of QRA in the oil and gas sector via the 'Risk Indicator Project' by Statoil and the Norwegian Petroleum Directorate, risk-monitoring indicators were subsequently developed based on QRA. As QRA was normally conducted for design process of a facility to assess the impacts of major modifications, it was deemed useful in capturing significant risk-contributing factors (Øien and Sklet, 1999). The 'Risk Indicator Project' also generated indicators for process accidents and blow out (Øien and Sklet, 1999) and addressed organizational risk factors such as training/ competence and work force engagement (Øien, 2001).

The sequel "Risk Level Project" conceded indicators for major accident risks, occupational accidents, diving accidents, working environment factors as well as other "Defined Situations of Hazard and Accident' (DSHA). DSHA includes hydrocarbon leaks, well kick, fire/ explosion in other areas and vessel on collision course (Petroleum Safety Authority Norway, 2009). These indicators marked an event-based approach in indicator development (Vinnem et al., 2006).

Indicators development associated with industrial safety has achieved substantial progress over the years much attributed to the early work in the nuclear industry. In addition, the use of leading indicators for safety performance measurement has received increasing attention due to a shift to proactive approach in safety management. Nonetheless, lagging indicators still get significantly more attention than leading indicators in corporate and facility-level safety reporting and performance management. The common lagging indicators often found in safety reports are number of fatalities, fatal accident rate, total recordable injury rate, lost time injury frequency and hydrocarbon releases (IOGP, 2016; NOPSEMA, 2015). Other indicators such as number of tier 1 process safety events and total recordable occupational illness frequency may be included in safety reporting of certain oil and gas companies. These indicators are also lagging in nature. Overemphasis on lagging indicators tend to shift focus away from underlying systemic failure, hence inability to fully reflect the current safety level of a facility. A typical example of accident resulting from over-reliance on lagging indicators is the Texas City Refinery accident (Baker, 2007) which killed 15 workers and injured more than 170. The accident investigation report revealed that the plant's management emphasized on personal safety such as slips and trips but failed to heed process safety and safety culture leading to build-up of technical and organizational failures such as defective alarms, corroded pipe and inadequate training (Baker, 2007). These 'hidden' failures escalated into the explosion of a hydrocarbon vapor cloud.

The limited usefulness of lagging indicators in capturing systemic defects resulted in the interest in leading indicators. Launching of the KP3 Asset Integrity program by the HSE UK marks an important effort in adopting leading indicators for industry-wide performance benchmarking (HSE, 2008). The program tracked progress of the participant oil and gas companies using KPIs related to maintenance and management of SCEs on their offshore facilities on the UK Continental Shelf. Participating companies adopted a set of SCEs recommended by the program and tracked compliance status of the SCEs using a traffic light system. Performance of asset integrity management was determined based on the number of compliance, isolated failure and non-compliance and is translated into three KPIs consisting of hydrocarbon releases, verification non-compliance and safety-critical maintenance backlog, to enable cross-industry performance comparison (HSE, 2009). The KPIs represent a continuum of leading and lagging indicators with KPI-1 hydrocarbon releases as the lagging indicator, KPI-2 verification findings as the intermediate indicator and KPI-3 safety-critical backlog as the leading indicator. The program engages participating companies in the regime of voluntary reporting of hydrocarbon releases wherein more details were collected concerning the releases (HSE, 2008; HSE, 2009).

Verification findings involve engagement of Independent Competent Person (ICP) to verify reports on monitoring and audit findings. ICP commonly reviews operator's inspection, maintenance and test records for SCEs and ranks criticality of the findings from 1 to 3 with 3 being the most significant finding which often leads to issuance of letter of reservation or concern to the operator (Jager, 2013; Frens & Berg, 2014). Being a leading indicator, KPI-2 also demonstrates lagging characteristics in the sense that raising a level 2 or 3 finding requires some form of failure. Safety-critical maintenance backlog monitors the effort channeled to inspection, testing and maintenance to ensure integrity of SCEs. Backlog of planned safety-critical maintenance is expressed in total man hours per month per installation (HSE, 2009).

Though not sufficiently addressing the organizational, human and personal aspects of safety, the program sets the path to performance measurement and benchmarking of asset integrity management across an industry and contributes to the use of more leading indicators for this purpose (HSE, 2008; HSE, 2009).

To date, the oil and gas sector continues to strive for improvement in safety performance measurement via refinement of indicator system. There are numerous guidelines for development of indicators for facilities posing major hazards such as explosion, fire and leakage. Five (5) important ones that are worth mentioning are:

1. Developing process safety indicators, by HSE (2006)
2. Guidance on developing safety performance indicators related to chemical accident prevention, preparedness and response for industry, by OECD (2008).
3. Process safety – recommended practice on key performance indicators, by IOGP (2011).
4. Process safety leading and lagging metrics, by CCPS (2011).
5. Process safety performance indicators for the refining and petrochemical industries, by API (2010).

A summary highlighting major comparison between the five guidelines is shown in **Table 2.1**.

Table 2.1: Comparison between the Major Guides for Safety Performance Indicators Development

	HSE (2006)	OECD (2008)	API (2010)	CCPS (2011)	OGP (2011)
Sector intended	Major hazard installations	Entities posing risk of major accident	Refining and petrochemical industries	Chemical and petroleum industries	Upstream oil and gas activities, e.g. exploration and production
Term used for safety indicators	Process safety performance indicators	Safety performance indicators	Process safety indicators	Process safety metrics	Key performance indicators (KPIs)
Approach/ type of indicators	Dual assurance, using both leading and lagging indicators	Outcome indicators and activities indicators	Tier approach*, from leading indicators at the bottom tier to lagging indicators at the top tier.	Tier approach, from leading metrics at the bottom tier to lagging metrics at the top tier. Use of "near miss" and other internal lagging metrics in between the topmost and bottommost tiers.	Tier approach, from leading indicators at the bottom tier to lagging indicators at the top tier. Tier 1 and 2 indicators are commonly used for corporate reporting while Tier 3 and 4 indicators monitor safety performance at facility level.
Classification of indicators	Based on organisational level, i.e.: 1. Corporate level indicators 2. Site level indicators	Based on critical areas, i.e.: 1. Policies, personal and general management of safety	Based on tier/ level of severity, i.e.: 1. Tier 1 – LOPC events of greater consequence 2. Tier 2 – LOPC events of lesser consequence	Based on tier/ level of severity, i.e.: 1. Tier 1 – Process safety incident 2. Tier 2 – Process safety event 3. Near miss	Based on tier/ level of severity similar to that of API's. Hierarchy of asset integrity KPIs in the guide demonstrates indicators

	HSE (2006)	OECD (2008)	API (2010)	CCPS (2011)	OGP (2011)
	3. Installation/ plant or facility level indicators	2. General procedures 3. Technical 4. External co-operation 5. Emergency Preparedness and Response 6. Accident/ near-miss reporting and investigation	3. Tier 3 – Challenges to safety system 4. Tier 4 – Operating discipline and management system performance indicators	4. Unsafe behaviours or insufficient operating discipline	classification based on organizational levels.
Metrics definition	Not specified	Five categories: 1. People 2. Organisations 3. System/ processes 4. Physical plant/ processes 5. Hazard and risk measures	Specific metrics provided e.g. For lagging indicators: 1. Tier 1 process safety event rate 2. Tier 1 process safety event severity rate 3. Number of safety instrumented system activations 4. Number of mechanical trip activation	Specific metrics provided e.g. For lagging indicators: 1. Total count of process safety incidents 2. Process safety total incident rate 3. Process safety incident severity rate For leading indicators: 1. Mechanical integrity	Examples of metrics provided e.g. For lagging indicators: 1. Tier 1 process safety event rate 2. Tier 2 process safety event rate For leading indicators: 1. Management and workforce engagement on safety 2. Hazard identification

	HSE (2006)	OECD (2008)	API (2010)	CCPS (2011)	OGP (2011)
			For leading indicators: 1. Process hazard evaluations completion 2. Process safety action item closure 3. Procedures current and accurate	2. Action items follow-up 3. Management of change	3. Competence of personnel

* A tier approach, unlike the approach based on critical areas, categorizes indicators into layers/ tiers with leading indicators representing inputs, efforts and measures channelled into a safety system at the bottom tiers. Failure of these indicators would eventually escalate into the lagging events such as LOPC (loss of primary containment), fatality and injury at the top tiers. The approach based on critical areas, however, classifies a mix of lagging and leading indicators based on critical areas such as procedures, emergency preparedness, hazard and risk assessment, etc.

2.8 Personal Safety Indicators for Offshore Oil and Gas Installations

At this point, a clear distinction has been drawn between process safety and personal safety. Governing different domains, the two types of safety merge at the occurrence of injuries and fatalities if not properly managed with process safety often causing more severe consequences for instance multiple fatalities. Both types of safety are founded on the common ground of leadership and management commitment (CSB, 2012).

The common personal safety indicators are recordable injury rate, lost time injury rate and days away from work (NOPSEMA, 2015; IOGP, 2016). As with process safety, leading and lagging indicators are increasing adopted for personal safety to monitor measures taken at personal level to prevent occupational incidents. Personal safety indicators are needed to ensure wellbeing of workers at workplace and to examine if duty of care has been sufficiently exercised in compliance with legal requirement. Personal safety is also crucial to maintain and improve work performance by reducing loss time cases and days away from work. Other than injury rates, personal safety indicators encompass occupational illness and poisoning, exposure to noise and chemicals hazardous to health, and at more refined level, ergonomics and fatigue (Flin et al., 2000; Ettorchi-Tardy et al., 2012). Fatigue-related impairment can adversely affect human performance, thus giving rise to safety concerns. The OGP-IPIECA (2012) published a guide on the performance indicators for fatigue risk management system. The performance indicators are developed based on two aspects, i.e. direct contributors to fatigue-related impairment and individual components of an effective fatigue risk management system. The direct contributors can be work-related encompassing facets such as rostered work hours, actual work hours, types of work tasks and working environment, as well as non-work-related such as amount of sleep and quality of sleep and sleeping environment (OGP-IPIECA, 2012).

There has been growing interest in ergonomics. Ergonomics aims to improve personal safety and increase overall performance of a system by modifying jobs, products, environments and systems to fit the needs and limitations of the operators (Canas et al., 2009). Inadequate ergonomic consideration causes occupational health and safety hazards, and decreased productivity (Shikdar & Sawaqed, 2004).

Psychosocial factors constitute another major facet of personal safety, or rather personal health, and deals with how culture, society, environment and mental processes affect a person's health. In an occupational setting, it relates to areas such as work arrangement and management, work demand, control at work, job satisfaction, social relationship, effort-reward imbalance, etc. (Clarke, 2006). Fatigue mentioned earlier is frequently a result of inadequate attention to psychosocial and ergonomic factors at work. Psychosocial factors, particularly overlap with the cognitive and organizational domains of ergonomics in the sense that cognitive ergonomics is connected to the psychology of a person and organizational ergonomics includes social interactions of a person with others in an organization (International Ergonomics Association, 2010). Mearns et al. (2010) reported that psychosocial risks in the oil and gas industry have significant health and safety implications and deserve similar attention as operational risks. Understanding the various domains of personal safety and health contributes to identification of lagging and leading indicators for the integrative safety performance measurement proposed in this study.

2.9 Composite Indicators for Safety Performance Measurement

As already mentioned, safety indicators are instrumental to any model of safety management system for performance management. The common performance areas and performance indicators for processes in the oil and gas industry, particularly the offshore sector have been reviewed. Of late, there is increasing interest in composite indicators which generate a performance index or score for a group of key indicators, thus providing an instant safety performance indication of a particular system.

Baker (2007) recommended the adoption of a single key composite indicator encompassing number of fires, explosions, loss-of-containment incidents and process-related injuries. Though focusing only on outcomes, it demonstrates the need to adopt a set of relevant indicators to effectively reflect the performance of safety system instead of a single indicator. Composite indicators provide immediate indication of a system's collective performance using a set of relevant sub-indicators which monitor the sub-domains of interest.

Composite indicators are adopted in the private and public sectors for performance measurement and comparison across sectors, nations or regions, for instance in the areas of sustainability, public services (Jacobs et al., 2004) and safety. In safety, sub-indicators constituting the composite value are either lagging indicators measuring incidents' frequency and severity (Venkataraman, 2008) or a combination of lagging and leading indicators (Walker and Cheyne, 2005). Though composite indicators present an uncomplicated way of performance measurement, derivation of weights during aggregation is often subjective as a result of insufficient data and knowledge in determination of weights. It is not uncommon to have performance measurement system that treats all indicators as having equal weight, but determination of indicators' weights enables vital indicators to have more impact on the compliance status of a system, thus, drawing due attention to these indicators (Saaty, 2008). Weight determination is frequently subject to individual or group influence wherein an indicator's value may affect or be affected by the actions of the individuals or groups (Hassan & Khan, 2012).

Selection of indicators precedes weight determination and should fulfill the criteria of SMART, i.e. specific, measurable, achievable, relevant and time-bound. A specific indicator is representative of the safety domain of interest with minimal vagueness. A measurable indicator is one which enables quantification via clearly defined measurement method. Achievable indicators usually have performance targets that are realistic, taking into consideration constraints that influence the outcomes. A relevant indicator is a valid indicator linked to actual practice and professional expertise with results reflecting the actual impact. Indicators which are timely enable progress to be tracked and impacts to be captured effectively. SMART can usually be achieved via identifying the issues of concerns, sourcing of established indicators from literature and guidelines, as well as inputs from industrial practitioners in screening the indicators (HSE, 2006; OECD, 2008).

There are several techniques of weight determination and the most common ones are analytic hierarchy process, conjoint analysis and survey weighting via expert or public opinion and factor analysis. AHP establishes a hierarchy of decision-making consisting of defined criteria which can be separately analyzed. Elements in the lower hierarchy have varying degree of influence on the elements in the hierarchy above. The degree of influence is established via pairwise comparison of elements in the lower hierarchy to determine their relative meaning and importance to the elements in the hierarchy above. The pairwise comparison to establish relative importance of elements is commonly conducted via questionnaire or experts' opinions (Saaty, 2008). AHP has been applied in multiple studies related to establishment of weights for contributors of safety performance. Ratnayake (2012) adopted AHP in deriving the weights of factors governing operational integrity. Podgorski (2015) also used AHP in selection of KPIs for operational performance measurement of occupational safety and health management system. Besides, Hassan & Abu Husain (2013) used AHP to determine the weights of indicators measuring asset integrity management performance of offshore floating facility which were later applied in aggregation to generate a composite performance indicator. Though AHP yields higher transparency and takes into account expert opinion, it requires a large number of pairwise analysis which complicates data collection, and requires elaborate computation, especially when large number of indicators are involved. The time and effort demanded for pair-wise comparisons of large number of criteria may pose constraints to experts' participation and the number of experts' responses acquired (Podgorski, 2015).

Conjoint analysis was initially developed as a quantitative marketing research tool which required respondents to complete a set of conjoint questions showing multiple attributes at a time. The reason is that decision-making often requires evaluation of the major attributes of a system or product collectively instead of individually. The attributes are varied independently. The most desirable attributes can be statistically deduced by observing the responses provided (Valeeva et al., 2005; Wu et al., 2014). Conjoint analysis yields preference scores also known as part-worth utilities for each level of attribute. Valeeva et al. (2005) applied conjoint analysis to identify the relative importance of food safety improvement attributes for pasteurized milk production. As the study did not intend to compare performance, no further attempt was made to derive a composite index. Bekar et al., used conjoint analysis to determine the statistical significance of performance measures for the effectiveness of total productive maintenance (TPM) implementation. Developed as a marketing research tool, conjoint analysis is commonly used to determine key attributes of a product that influence customers' choice, ranging from the selection of subcompact cars (Wu et al., 2014) to preference of performing arts tourism products (Kim et al., 2016). While conjoint analysis produces weights with trade-offs captured in respondents' preference for criteria or indicators, it involves certain level of complexity, for instance the use of utility and set-up of survey instruments, to garner responses and the weight estimation process is complex (Jacobs et al., 2004). Complexity of survey set-up and computation increases with the number of indicators involved.

Alternatively, survey can be conducted to gather perceptions of respondents on the importance and other crucial domains of the elements. A survey involves the use of questionnaire and a rating system or metric for the survey items. This allows responses to be collected from a larger number of participants or experts in an uncomplicated way. Selection of respondents can be random or stratified depending on whether responses from the public or a specific group of individuals are required (Bradburn et al., 2004). Dejoy et al. (2004) employed five-point Likert scale to determine the relative importance of safety climate determinants and concluded that environmental conditions, safety policies and programs and organizational climate are the three major determinants of safety climate. Verma and Pullman (1998) used questionnaire with Likert scale to investigate how managers perceived the importance of different supplier attributes. Likert scale was also used to identify the perceived importance of items affecting attractiveness of medical tourism with the ratings forming the basis of subsequent development of medical tourism index to measure how attractive a country is for medical tourism (Fetscherin & Stephano, 2016).

Scores of sub-indicators of a composite indicator are commonly aggregated by means of arithmetic, geometric or harmonic. Arithmetic aggregation, also known as linear aggregation is the simplest aggregation method where all sub-indicators have the same measurement unit and the composite indicator's value is derived from the weighted or ordinary mean of the sub-indicators, depending on whether relative importance of the indicators is taken into consideration (Ravana & Moffat, 2009). Composite value with defined range can also be generated from standardized scale. Geometric aggregation does not require the sub-indicators to have the same measurement units because the aggregation is fundamentally the multiplication of a set string of, say t, numbers followed by t^{th} root of the multiplication value. For instance, it is possible to aggregate volume, length and weight, using the geometric mean in the manner of (liters x centimeters x kilograms)$^{1/3}$. As such geometric mean is less susceptible to values falling far from the mean, than arithmetic means. The harmonic means, on the other hand, is the 'reciprocal of the average of reciprocals' as shown in the formula in **Table 2.2** (Ravana & Moffat, 2009).

Table 2.2: Common Methods of Aggregation

Aggregation Method	**Mathematical Equation**
Arithmetic Mean	$\frac{(\sum_{i=1}^{t} x_i)}{t}$ with $\{x \mid i \in 1 \ldots. t\}$
Geometric Mean	$(\prod_{i=1}^{t} x_i)^{1/t}$ with $\{x \mid i \in 1 \ldots. t\}$
Harmonic Mean	$\frac{t}{\sum_{i=1}^{t}(\frac{1}{x_i})}$ with $\{x \mid i \in 1 \ldots. t\}$

Note: $\{x \mid i \in 1 \ldots. t\}$ stands for a set of t observations

The emergence of fuzzy logic provides an avenue for aggregation of indicators to yield a composite. Fuzzy inference system, particularly enables experts' experience to be recorded in the form of rules which form the basis of decision making. Fuzzy logic finds wide applications even in multi-criteria decision-making (MCDM) where a combination of fuzzy inference system and fuzzy AHP had been used by Yang et al. (2011) to derive the importance scores for prioritization of environmental issues in offshore oil and gas operations. A detailed account of fuzzy logic and fuzzy inference system is provided in the subsequent section.

2.10 Integration of Fuzzy Inference System in Safety Performance Measurement

Fuzzy logic is founded upon the concept of graduation and granulation with a variable of interest graduated into varying degrees, hence the term fuzzy. Granulation refers to the clustering of attribute-values based on their similarity or functionality. Fuzzy logic, therefore, operates by means of graduated granulation or fuzzy granulation akin to how human makes complex decisions with incomplete information (Zadeh, 2008). Linguistic variable widely used in practical aspects of fuzzy logic is a typical example of granulation and is related to the concept of granular value. For instance, a variable, A is a subset of B with its elements defined by B, and c is a numerical element of A. c is a singular or point value of A if it is precisely known (refer **Figure 2.5**). In the case if A is not well defined, what is known about c contributes to the definition of A, for instance, if c is known to be a value between a and b, then [a, b] is considered a granular value of A. A granular variable is, therefore, characterized by granular values. A linguistic variable is essentially a granular variable expressed in language rather than number (Zadeh, 2008)

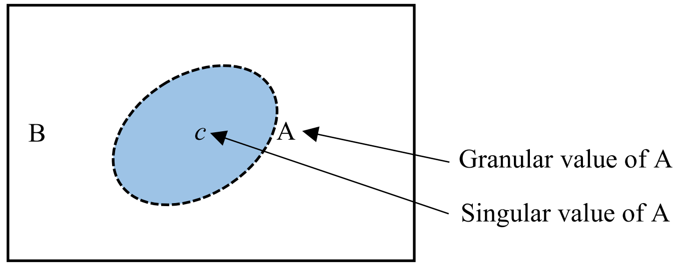


Figure 2.5: The Concept of Granular Variable (Zadeh, 2008)

Fuzzy inference system is based on fuzzy logic developed by Lofti Zadeh in 1965, aiming to generate inference and knowledge from uncertainty and imprecision via computational methods (Zadeh, 2008). It has since found applications in the development of industrial controllers (Bandermer & Gottwald, 1995; Klir & Yuan, 1996) and other fields including engineering, mathematics and computer science (Sinha & Gupta, 2000).

The fuzzy inference system is essentially the application of fuzzy logic and is otherwise known as fuzzy expert system. It is founded on the if-then rules established from expert knowledge. A diagrammatic representation of the fuzzy inference system is shown in **Figure 2.6.** The system commences with crisp or numerical inputs which are fuzzified into linguistic inputs as defined by input membership functions. The rule base represents a set of linguistic if-then rules contributed by experts which convert the fuzzy input into fuzzy output. The fuzzy outputs are dictated by the rule strengths and output membership functions. Defuzzification interface then converts the fuzzy outputs into crisp values (Azadeh et al., 2015).

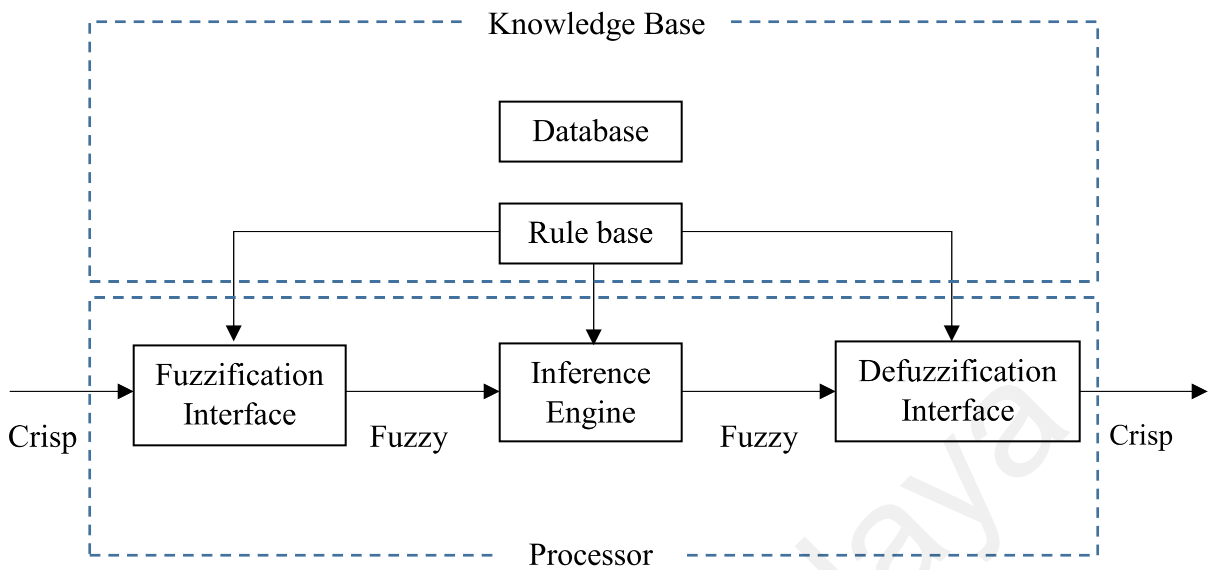


Figure 2.6: Fuzzy Inference System (FIS) (Azadeh et al., 2015)

Fuzzy logic has been adopted in various aspects of safety. In risk assessment for instance, Bowles and Pelaez (1995) incorporated fuzzy logic in Failure Mode, Effect and Criticality Analysis (FMECA) where the three variables in failure assessment, i.e. severity, frequency of occurrence and detectability were transformed into membership functions of a fuzzy set. Markowski and Mannan (2009) also applied fuzzy logic in determination of the frequency and severity, hence risk level in piping risk assessment by relating crisp numbers of the functions to linguistic variables. Xu et al. (2002) combined fuzzy logic with failure mode and effect analysis (FMEA) using an approach similar to that of Bowles and Pelaez (1995) for diesel engine's turbocharger system.

Fuzzy logic is also used in combination with other methods such as Bayesian network and probabilistic models in risk assessment. Lavassani et al. (2011) employed fuzzy logic in derivation of basic risk item from the likelihood and consequence of a failure, for risk evaluation of offshore wells. Eleye-Datubo et al. (2008) proposed the integration of fuzzy logic with Bayesian network to incorporate human elements into risk modelling for marine and offshore safety assessment where fuzzy logic was used to determine human performance based on performance-shaping factors.

Despite being a subset of safety, unlike risk assessment, safety performance evaluation focuses on continuously monitoring and assessing the safety performance of a system using a set of relevant criteria called key indicators with risk assessment often being one of the key indicators (Azadeh et al., 2008). Instead of looking into how risk assessment is conducted, it examines how well risk assessment is conducted. Fuzzy logic has also been employed in safety performance. Bao et al. (2012) proposed a hierarchical fuzzy TOPSIS model to derive the weights for road safety performance indicators in yielding a composite road safety performance index. Ma et al. (2011) used Fuzzy Delphi Method and Grey Delphi Method to determine road safety performance indicators. Sun (2010) proposed a performance evaluation model applying both fuzzy AHP and fuzzy TOPSIS in determining the weights of performance criteria and the best alternatives which fulfill most of the desirable criteria respectively. Zheng et al. (2012) utilized trapezoidal fuzzy to derive the weights of the respective work, environment and human safety indices for evaluation of work safety in hot and humid environments. These studies share the similarity of applying fuzzy logic in determining the criteria and their weights for performance evaluation, with limited attempt to actually employ fuzzy logic as the core of performance evaluation.

Other than relevant criteria and weights, fuzzy performance evaluation relies on expert rules for decision-making (Bellochi, 2002). Fuzzy inference system is, therefore, central to the practice of performance evaluation. Azadeh et al. (2008) designed a fuzzy expert system to assess the health, safety, environmental and ergonomics factors in a gas refinery. Bellocchi et al. (2002) proposed a fuzzy expert system to assess the performance of solar radiation models. Despite its diverse applications, the use of fuzzy expert system in safety performance evaluation of offshore oil and gas platform has not been subject to extensive studies. Yang et al. (2011) employed fuzzy expert system and fuzzy analytic hierarchy process to weight environmental issues associated with offshore oil and gas operations but did not attempt to evaluate the environmental performance of the operations based on the issues. Therefore, the adoption of fuzzy inference system in this study provides an avenue to combine the various safety indicators from fragmented safety practices of the offshore oil and gas sector, with expert rules to yield a single safety composite index for the platform, represented by a linguistic output (Kwong et al., 2002). This is instrumental to highlight the 'health' of a platform, providing immediate warning in the case of deviation from operational norms, thus enabling timely corrective measures to be initiated.

Fuzzy inference system provides the dynamism and flexibility in safety performance management where rules of evaluation and targets of indicators can be altered in line with organizational goals and as part of continuous improvement (Yang et al., 2011). According to Azadeh et al. (2008), fuzzy inference system is crucial in promoting close monitoring of safety performance and problems by managers which enables timely corrective actions. This is due to the ability of fuzzy inference system to provide real-time analysis and feedback, thus, enabling effective decision-making and up-to-date improvement. Incorporation of fuzzy inference system and key indicators in the safety performance measurement of offshore platforms' operations could potentially enhance the effectiveness of safety management on the Malaysian offshore oil and gas platforms.

The fuzzy inference system has been compared with the radial basis function networks as a potential inferencing engine. The comparison shows two techniques which are fundamentally different. Irdi et al. (2008) reported that fuzzy inference system and radial basis function networks (RBFN) only demonstrate functional equivalence under certain conditions, i.e. 1) it only applies to Takagi and Sugeno types of fuzzy inference system with a constant output, 2) Gaussian functions with the same variance is selected as the membership functions, 3) the number of rules in the inference system equates the number of receptive field units of the RBFN, 4) same method of deriving the outputs is used in both method. In this study, the outputs are safety compliance states of an offshore platform which are not represented by a constant, but a crisp output indicating varying degree of compliance. In addition, membership functions used for the input and output variables are of trapezoidal and triangular types instead of Gaussian.

RBFN is a type of artificial neural network with activation functions being radial basis functions. It generates a linear output from neuron parameters and inputs with radial basis functions. Fuzzy logic has been linked to neural network in adaptive neuro-fuzzy inference system (ANFIS). ANFIS facilitates determination of task-relevant fuzzy decision rules via feed forward network. Input and output dataset enables ANFIS to adjust membership functions of a fuzzy inference system, thus permitting the system to learn. Azadeh et al. (2013) employed ANFIS to develop an intelligent algorithm which evaluates stress level of operators in noisy and complex petrochemical plants. ANFIS requires training data to generate a numerical output via Takagi-Sugeno fuzzy model. Unlike the study of Azadeh et al. (2013), this study proposes a new performance measurement framework for offshore oil and gas platforms. The output is primarily linguistic though safety scores of the platforms can also be computed. Besides, output data for ANFIS training is not available which rules out the use of ANFIS in this study.

2.11 A Lack of Integrative Safety Performance Measurement Framework for Offshore Oil and Gas Platforms

In light of the hazards related to offshore oil and gas platforms and the promulgation of an integrative safety management approach on the platforms to enable more efficient highlight of a platform's status in addition to providing reliable early warning signals, it is crucial to have a safety performance measurement framework for offshore platforms. An established framework also facilitates performance comparison and benchmarking, thus, promoting a learning culture.

Hassan & Khan (2012) developed a composite asset integrity indicator which integrates mechanical, operational and personnel aspects via aggregation method. They identified approximately 40 indicators categorized under the respective domains of mechanical, operational and personnel but did not cover certain crucial aspects of safety such as documentation, change management, personal safety and contractors' safety. The composite indicator shows risk index rather than performance index.

Bergh et al. (2014) identified a set of indicators to monitor psychosocial risk in the oil and gas sector but did not attempt to yield a composite index from the indicators. In addition, the indicators only focus on a specialized area of personal safety without attempting to integrate major safety aspects of offshore oil and gas operations. Zhang et al. (2016) proposed a safety evaluation index system to capture the performance of static and dynamic equipment as well as management such as faulty operation and insufficient quality in oil and gas production plants. The study was primarily hardware oriented and focused on weight distribution rather than performance evaluation using fuzzy inference system.

Rui et al. (2017) developed a set of metrics for evaluation of offshore oil and gas project based on five criteria, i.e. safety, production, quantity, cost and schedule. The evaluation system examines project deficiencies and aims to improve project performance, with safety being a criteria. The safety indicators comprising total recordable incident rate, lost time case rate and fatality rate, are simplistic and look only into limited facets of safety. Landucci et al. (2015) proposed a quantitative assessment to evaluate performance of safety barrier in thwarting fire escalation. The study is specific to a particular aspect of safety and limited to assessment of single safety critical element. It has a different direction from integrative safety study, as in this work.

The previous section mentioned the framework of Azadeh et al. (2008) to evaluate the health, safety, environmental and ergonomics factors in a gas refinery using fuzzy expert system. The study intended for gas refinery had included limited indicators of health and safety for instance, accident severity rate, accident frequency rate and medical surveillance. Without including the crucial safety aspects of offshore oil and gas operations, it has limited usability to evaluate safety performance of offshore oil and gas platforms.

There is an apparent lack of integrative safety performance evaluation framework encompassing the important safety domains for offshore oil and gas platforms. The current frameworks focus on the lagging aspects of performance as well as particular areas of safety such as safety culture and organizational factors without attempting to integrate most, if not all crucial aspects of offshore platforms' safety by leveraging on the experiences of the local expertise. The safety performance criteria adopted are usually treated as equally important and limited attempts were made to derive weights which reflect relative importance of the indicators.

The literature review also revealed very limited correlational studies among the safety factors studied which can shed important insight into the synergy between the safety factors, hence enabling better predictions of the performance of safety factors and overall safety performance. Studying their correlations also contribute to causational understanding of how leading factors affect lagging factors such as fatalities, near-misses and injuries.

Besides, the literature also shows a shortage of study done on regional scale for development of safety indicators and performance evaluation framework which draws on specific local knowledge and expertise. Incorporation of regional knowledge and requirements into such framework will contribute to more effective regional safety performance management.

CHAPTER 3: METHODOLOGY

3.1 Overview

The study involves compilation and selection of a list of safety indicators to measure the safety performance of offshore oil and gas installations via literature review and consultation with industrial practitioners. The safety indicators were grouped under 14 safety factors based on literature review and opinions of industrial practitioners.

The indicators were transferred into a preliminary questionnaire consisting of two main sections to investigate the importance of the safety indicators and the perceived risk resulting from failure to observe the indicators. The preliminary questionnaires were administered to 20 industrial practitioners and academic staff in a pilot study to validate the survey items. Internal consistency of the survey items was measured using Cronbach's α (Dahl & Olsen, 2013; Goforth, 2015).

Initial checking and screening of the survey items were also conducted during the process to improve clarity and relevance of the survey items (Mearns et al., 2010). The pilot study yielded a final questionnaire with a list of 70 safety indicators grouped under 14 safety factors. 250 questionnaires were sent out to the safety and health department of 10 major oil and gas companies in Malaysia to gather responses from health and safety practitioners, ideally those with offshore experience, concerning their perceived importance of the safety indicators and perceived risk due to failure to observe the indicators. This aimed at leveraging the experience of the health and safety personnel in identifying safety indicators which are most pertinent to the Malaysian offshore oil and gas sector. The data were analyzed statistically to demonstrate descriptive statistics of the safety indicators and correlations of the overarching safety factors in terms of perceived importance and perceived risk due to indicator's failure.

The perceived importance and risk ratings were then used to generate the weights of the safety indicators in safety performance measurement of offshore oil and gas installations (Olson et al., 1985; Rundmo, 1994; Rundmo, 1995). A traffic light system conventionally used in asset integrity management of the oil and gas sector was adopted in safety performance measurement of the offshore platforms using the safety indicators identified and the weights determined from the survey above. Traffic light system consists of three colors representing three status of compliance with red representing non-compliance, amber indicating isolated failure and green representing compliance. To enable score generation using this safety performance measurement framework, the traffic light system was modified by replacing the compliance status with numbers where 0 represents no data collected, 1 represents non-compliance, 2 represents isolated failure and 3 compliance (HSE, 2008).

By multiplying the weight and score of an indicator, the compliance score of the indicator can be obtained. Score of a safety factor is the sum of compliance scores of its underlying indicators. Safety factor score serves as the input of a fuzzy inference system incorporated into the framework to garner expert's judgement and experience in determining the final status of an offshore platform (Podgorski, 2015). The input variables consist of safety factors with membership functions representing three linguistic values, i.e. compliant, deviated and non-compliant. This is in line with the numbered traffic light system to indicate the compliance status of an indicator, hence the safety factor. The range of values for membership functions representing the states of compliant, deviated and non-compliant respectively were determined from the corresponding scores of the states. (Yang et al., 2011; Sa'idi et al., 2014).

Three scenarios of membership functions were tested. Rules proposed qualitatively by the industrial practitioners were entered into the fuzzy inference system. From the inputs comprising the respective scores of the 14 safety factors, the system generates a single output showing the safety performance status of the facility in four levels, i.e. compliant, slightly deviated, highly deviated and non-compliant, as well as an aggregated performance score of the facility.

The safety performance measurement framework was tested with actual safety performance data of offshore oil platforms obtained from the industrial practitioners participating in this study to determine its applicability and ability to predict actual performance (Azadeh et al., 2008). This also permits continuous improvement of the framework to increase its relevance to offshore operations. A flow diagram for identification of safety factors and indicators for offshore oil and gas installations is shown in **Figure 3.1**.

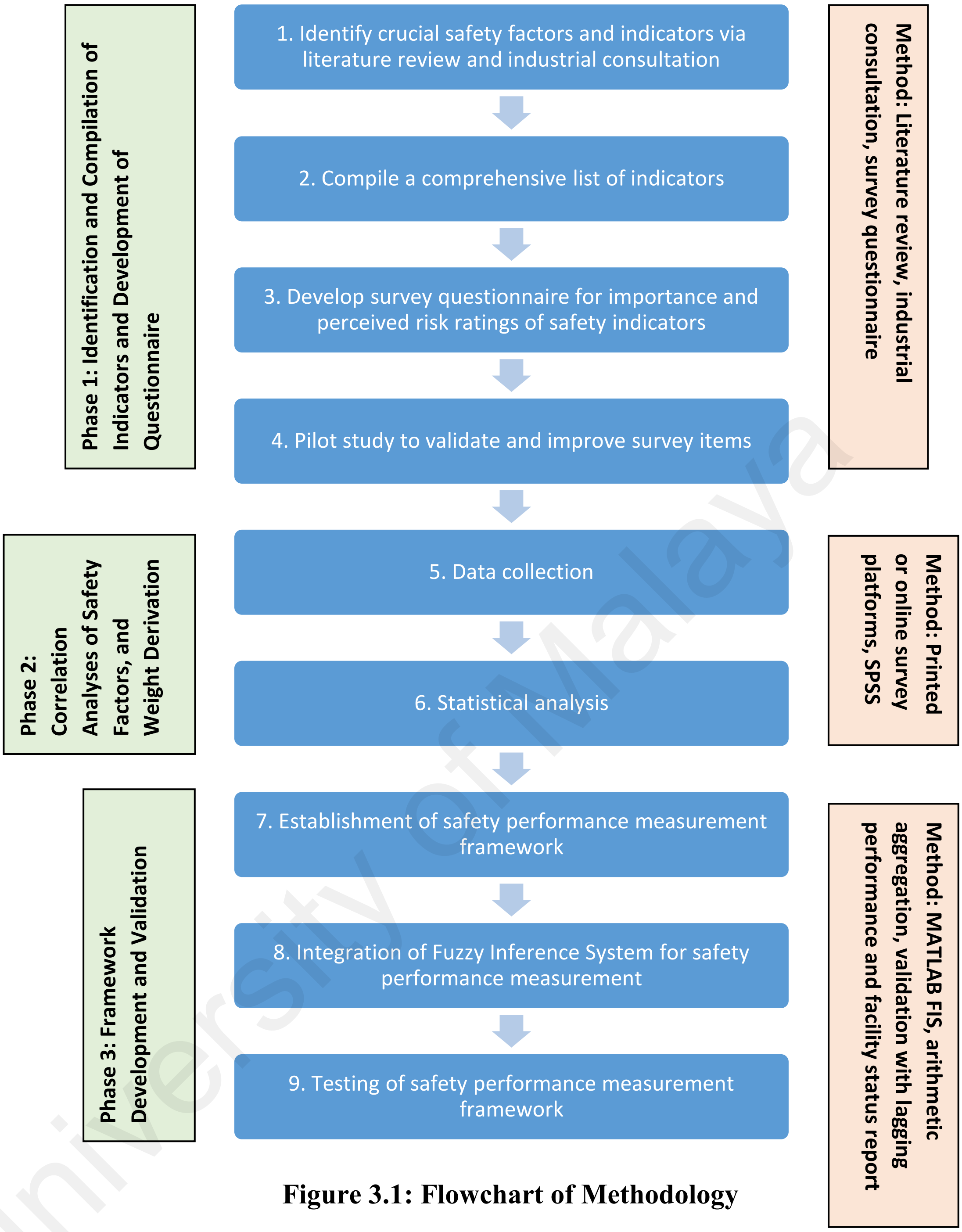


Figure 3.1: Flowchart of Methodology

3.2 Conceptual Framework

The basis underlying the study is that off-the-shelf safety performance indicators for offshore oil and gas installations may have limited effectiveness in monitoring safety performance without considering the specific legislative and operational requirements of the installations. Involvement of industrial practitioners via consultation and survey is therefore crucial in identification of safety performance indicators most pertinent to the offshore oil and gas operations in Malaysia (Azadeh et al., 2008; Azadeh et al, 2015). The indicators should encompass the major areas of safety i.e. process and personal safety using both lagging and leading indicators (Hopkins, 2009). A combination of leading and lagging indicators ensure not only the outcomes of safety management system are monitored but input and effort channeled into the system (HSE, 2006; Øien et al., 2010; Øien et al., 2011; Leveson, 2015).

The indicators covered the major attributes of safety, particularly safety climate, organizational factors (Vinnem, 2010), resilience engineering (Sarshar et al., 2015) and elements of the Operational Condition Safety (OTS) model proposed by Sklet et al. (2010) based on quantitative risk assessment (QRA) in the offshore oil and gas sector. The literature reviewed covers primarily areas as shown in **Figure 3.2**.

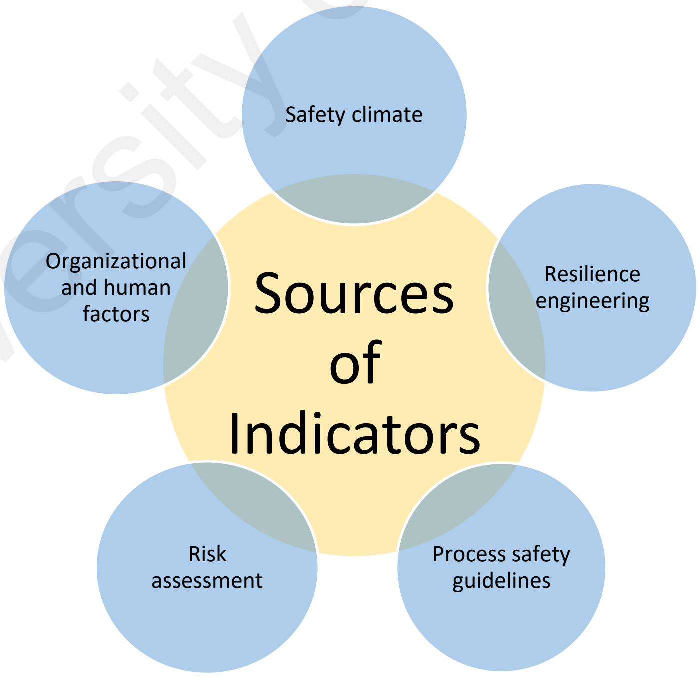


Figure 3.2: Classification of Literature from which Indicators were Sourced (HSE, 2009; Sklet et al., 2010; Vinnem, 2010; Leveson, 2015; Sarchar et al., 2015)

The areas in **Figure 3.2** reflect the major sources of indicators for offshore safety. For instance, the process safety guidelines were reviewed as they provide industry-related indicators to capture the performance of main offshore safety domains. Risk assessment also forms a critical aspect of the offshore safety to ensure the major risks have been identified, assessed and control via instruments such as process hazard analysis while organizational and human factors focus on management's engagement, competence building and reducing human errors which are deemed to play crucial role in offshore safety.

The weights of the safety indicators identified from the questionnaire survey represent the perception and opinion of the safety practitioners in the Malaysian oil and gas sector in terms of indicators' importance and risk associated with failure to observe the indicators. This permits the indicators to be differentiated from the generic ones with weights often undefined.

The weights and compliance status of safety indicators form the basis of the safety performance measurement framework. The score of each safety factor is calculated by summing the products of weights and 'compliance number' representing compliance status of the underlying indicators. The scores of safety factors are the input of a fuzzy inference system integrated into the framework. Rule-setting for the fuzzy inference system enables importance of the safety factors to be captured in determining the overall compliance of an offshore platform's safety system. A diagrammatic representation of the theoretical framework is shown in **Figure 3.3**.

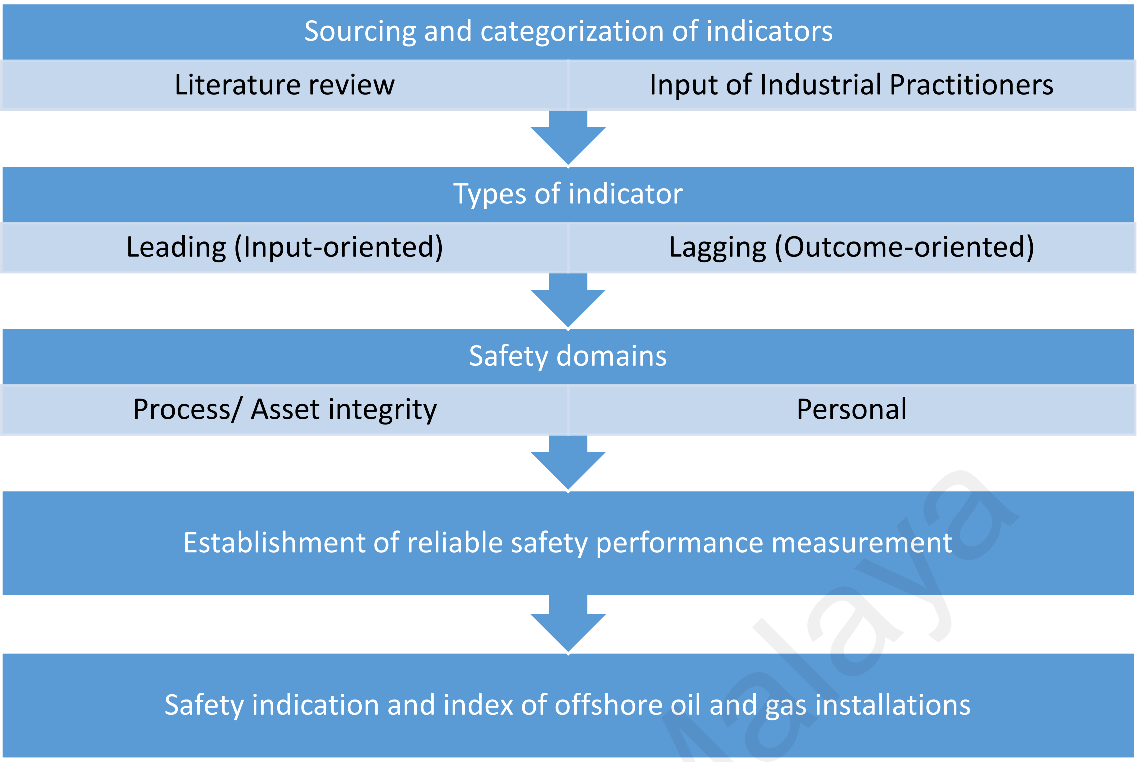


Figure 3.3: Conceptual Framework of Study

3.3 Identification and Compilation of Crucial Safety Factors and Indicators

Safety indicators for offshore oil and gas platforms were identified mainly via literature review and consultation with industrial practitioners participated in the study. The literature reviewed includes widely used guidelines for development of indicators published by health and safety authorities across different nations, and papers in relation to offshore safety indicators encompassing safety climate, resilience engineering and risk-based indicators, among others. The major guidelines reviewed are listed below:

1. Developing process safety indicators – A step-by-step guide for chemical and major hazard industries by HSE (2006)
2. Guidance on developing safety performance indicators related to chemical accident prevention, preparedness and response by OECD (2008)
3. Process safety – recommended practice on key performance indicators by OGP (2011)
4. Process safety leading and lagging metrics by CCPS (2011)

5. Process safety performance indicators for the refining and petrochemical industries by API (2011)

The indicators were selected based on: 1) their relevance to offshore installations, processes and work environment (refer to Step 1 in **Figure 3.1**) because there are indicators which address the petroleum and chemical sectors in general and the indicators need to be screened so that indicators catering only for offshore safety are chosen; 2) opinions of participating industrial practitioners as they provided their valuable inputs to the selection and addition of indicators based on work experience; 3) the measurability of indicators because not all indicators can be satisfactorily measured particularly those addressing safety culture and climate; 4) attainability of the indicators in view of the existing offshore safety data collection regime and this also relies on the inputs of the industrial practitioners; 5) the adoption of both leading and lagging indicators for proactive and reactive safety performance monitoring.

The A total of 73 safety indicators and 15 safety factors were initially identified. The indicators were then grouped under 14 safety factors respectively with reference to literature and suggestions by industrial practitioners. The list of safety factors and the number of indicators thereunder are shown in **Table 3.1**. The list of indicators is attached in **Appendix A**.

Table 3.1: Safety Factors, Number of Safety Indicators and Their Sources

No.	Safety Factors	Number of Indicators	Sources of Indicators
1	Management and Work Engagement (MWE) on Safety	4	Gadds & Collins, 2002 Sklet et al., 2010 Cox & Cheyne, 2010 OGP, 2011 Vinnem, 2010 Morrow et al., 2014
2	Inspection and Maintenance	12	Øien and Sklet, 1999 HSE, 2006 HSE, 2008 OECD, 2008 API, 2011 CCPS, 2011 Øien et al., 2011 OGP, 2011 CSB, 2012 Reiman & Pietikainen, 2012 Podgorski, 2015 Sarshar et al., 2015 Potty & Mohd. Kram, 2009
3	Competence	4	Wreathall, 2006 Vinnem et al., 2006 API, 2011 CCPS, 2011 Øien et al., 2011

No.	Safety Factors	Number of Indicators	Sources of Indicators
			OGP, 2011 Reiman & Pietikainen, 2012 Leveson, 2015
4	Operating Procedures (This is merged with 'plant operation' based on suggestion by industrial practitioners	4	Øien & Sklet,1999 HSE, 2006 OECD, 2008 CCPS, 2011 API, 2011 OGP, 2011 Reiman & Pietikainen, 2012 Mannan, 2014
5	Instrumentation and Alarms	5	Beard & Santos-Reyes, 2003 Baker, 2007 HSE, 2006 API, 2011 OGP, 2011 Inputs of industrial practitioners
6	Plant Change/ Management of Changes (MOCs)	7	HSE, 2006 Baker, 2007 OECD, 2008 Sklet et al., 2010 API, 2011 CCPS, 2011 OGP, 2011 Reiman & Pietikainen, 2012 Lauder, 2012

No.	Safety Factors	Number of Indicators	Sources of Indicators
7	Plant Design	4	Chia et al., 2003 HSE, 2006 Woods, 2006 OECD, 2008 OGP, 2011 SINTEF, 2012 Rathnayaka, 2014
8	Plant Operation (This is merged with 'operating procedures' based on suggestion by industrial practitioners	7	Øien and Sklet, 1999 OECD, 2008 CCPS, 2011 OGP, 2011 Øien et al., 2011 Lavasani et al., 2011 Skogdalen et al., 2011 Reiman & Pietikainen, 2012 Swuste, 2016
9	Start-ups and Shutdowns	3	Vinnem et al., 2006 OECD, 2008 OGP, 2011 CSB, 2012 Lauder, 2012 Inputs of industrial practitioners
10	Emergency Management	5	HSE, 2006 OECD, 2008 Øien, 2008 Vinnem, 2010

No.	Safety Factors	Number of Indicators	Sources of Indicators
			API, 2011 CCPS, 2011 OGP, 2011 SINTEF, 2012 Inputs of industrial practitioners
11	Hazard Identification and Risk Assessment	3	OECD, 2008 OGP, 2011 API, 2011 Lauder, 2012 Reiman & Pietikainen, 2012 Kannan et al., 2016
12	Documentation	2	OECD, 2008 Costella et al, 2009 Whewell, 2012
13	Contractor Safety	3	OECD, 2008 Hassan & Khan, 2012 Rui et al., 2017 Inputs of industrial practitioners
14	Personal Safety	9	FMA, 1967 OSHA, 1994 OECD, 2008 ANSI/API, 2011 CCPS, 2011 IPIECA-OGP, 2012 Inputs of industrial practitioners

No.	Safety Factors	Number of Indicators	Sources of Indicators
15	Number of Incidents and Near Misses	1	HSE, 2006 Reiman & Pietikainen, 2012 Zhang et al., 2016
	Total	73	

Initial screening yielded 70 safety indicators. 5 of the 73 indicators were omitted due to repetition and ambiguity, as indicated in **Appendix A** and Indicator 20 was broken down into 3 separate indicators (**Appendix A**). The safety factors 'plant operation' and 'operating procedures' had been merged as 'operation and operating procedures' and a new safety factor, i.e. 'personal safety' was included as suggested by industrial practitioners. The indicators include both leading and lagging indicators covering personal safety and various aspects of process safety.

3.4 Development of Questionnaire

A questionnaire was subsequently developed based on the list of indicators to investigate the importance of the safety indicators identified (refer to Step 3 in **Figure 3.1**). A sample of the questionnaire is attached in **Appendix B**.

The questionnaire consisted of 3 parts. The first part gathered basic demographic information of respondents, i.e. the name of the company, the position held and the year of experience, using open-ended questions. The second part required the respondents to rate their perceived importance of the safety indicators on the Likert scale. Likert scale was chosen due to its simplicity, potential for quantification, ease of comprehension and consideration for neutral or undecided responses (Bradburn et al., 2004). The scale ranged from 1 to 5 in the order of increasing importance.

In the third section, the respondents were required to rate their perceived risk arising from failure or negligence in observing the indicators on a Likert scale ranging from 1 to 5 with increasing perceived risk. Perceived risk took into consideration the likelihood and severity of incident occurrence. The Likert/ survey items for the second and third parts of the questionnaire are close-ended to enable rating using the Likert scale.

Validity of questionnaire is crucial prior to dissemination to gather responses. A valid questionnaire measures the intended concept accurately. In this study, the fundamental concept comprises specific and relevant safety indicators correctly grouped under the corresponding safety factors for safety performance measurement of offshore oil and gas installations in Malaysia. The survey items should present the relevant safety indicators correctly matched with the safety factors.

The questionnaire was developed to meet the following validity:

a. Face Validity

Face validity is conferred by assessors based on their evaluation in relation to the ability of the survey items to capture the concept measured adequately. It is non-statistical. Where face validity is concerned, the concept measured must be well-defined and the information gathered must be relevant to the concept (Bradburn et al., 2004). To obtain face validity, the safety factors were determined in relation to literature review and consultation with industrial practitioners, focusing mainly on the domains of personal safety and process safety.

b. Content Validity

Content validity is another non-statistical attribute of validity. It involves systematic examination of the empirical indicators/ survey items to ensure they are representative of the domain or concept measured. It is based on subjective judgement of the researcher and industrial practitioners, as well as literature review (Bradburn et al., 2004; Foxcroft et al., 2004). Safety indicators constituting the survey items were derived from literature review and industrial practitioners. The questionnaire was evaluated by industrial practitioners and pilot test subjects to ensure content validity (Bradburn et al., 2004). While face validity confers validation of the overall concept studied, content validity delves into specific contents under the concept of interest.

c. Criterion-related Validity

Also known as concurrent validity, predictive validity or external validity, this dimension of validity concerns the extent to which a measuring questionnaire is related to an independent measure of the relevant criterion. In other words, it refers to how relevant the survey findings are to the "real world" (Rattray & Jones, 2007). This involves making relation between a survey finding and an actual scenario (Shannon et al., 1997). Criterion-based validity was conducted in the final stage of the study where the safety performance measurement framework was validated against actual safety data of offshore oil platforms to examine whether and in what manner the measurement results generated by the framework were representative of the actual safety performance.

In addition to being valid, a questionnaire needs to be reliable. Reliability means the ability of the questionnaire to yield consistent result. Conventionally, Cronbach's α is used to measure reliability of a questionnaire or more specifically the internal consistency aspect of reliability. Cronbach's α indicates the correlation of survey items as a group, or the uni-dimensionality of the survey items. Higher value of alpha indicates higher inter-relatedness of the survey items (Goforth, 2015). The formula for Cronbach's α is shown in **Equation 3.1**:

$$\alpha = \frac{K}{K-1}\left(1 - \frac{\sum_{i=1}^{K}\sigma_{Yi}^2}{\sigma_X^2}\right) \quad \textbf{(3.1)}$$

where K = number of scale items, σ_{Yi}^2 = variance associated with item i, and σ_X^2 = variance associated with the observed total scores.

The formula demonstrates that Cronbach's α correlates the score or rating of a survey item to the summed score or rating of each completed survey and compares the correlation to the variance of summed score or rating of individual survey items (Goforth, 2015).

3.5 Pilot Study

A pilot study was conducted to screen, validate and improve the survey items (Hassan & Khan, 2012) (refer to Step 4 in **Figure 3.1**). The first phase of the pilot study involved dissemination of the survey questionnaires to 10 oil and gas industrial practitioners participated in the study for checking and screening to ensure face and content validity, hence increasing representativeness of survey items to the domain or concept measured (Foxcroft et al., 2004).

During screening, the participants provided further feedback on redundant indicators measuring repeating and irrelevant aspects which were not detected during initial screening. The participants also commented on the grammar, sentence structure and clarity of the survey items. Screening during the pilot study resulted in minor shifting of the survey items from one safety factor to another, minor change in sequencing of the survey items and rephrasing of survey items to enhance clarity and ease of understanding. The number of safety indicators and safety factors remained unchanged after the pilot study screening.

The finalized survey questionnaire was then validated by administering a trial survey among 20 industrial practitioners of different oil and gas companies and academic staff. Reliability of the survey items were measured using Cronbach's α.

A flowchart of the questionnaire construction and validation process is shown in **Figure 3.4**.

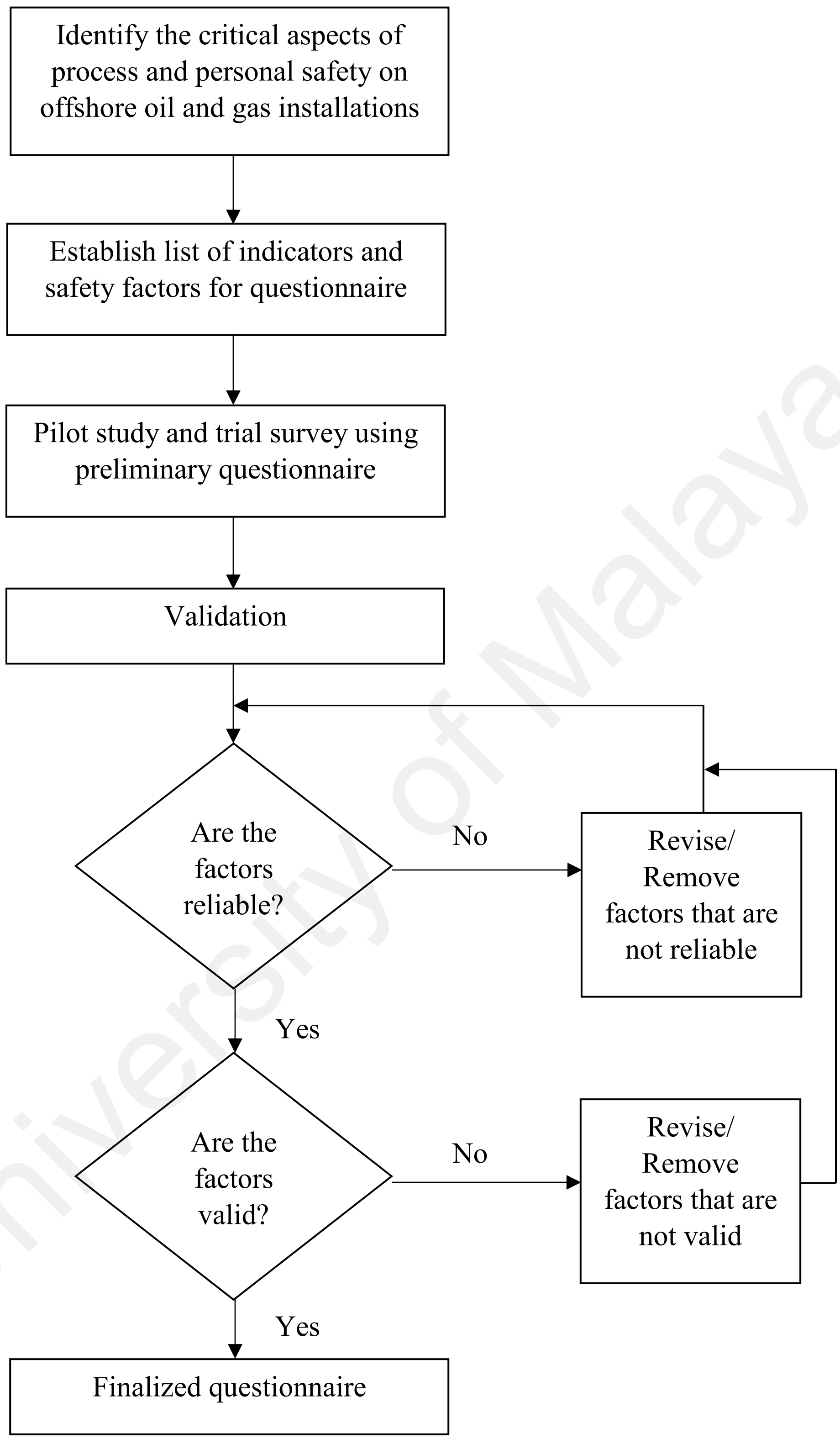


Figure 3.4: Questionnaire Construction and Validation Process

3.6 Data Collection

Responses were collected via mixed mode method (refer to Step 5 in **Figure 3.1**). 250 questionnaires were sent via online survey platform, as well as face-to-face, email and postal methods. The targeted respondents consisted of health and safety professional at various levels of seniority in the oil and gas sector who ideally had experienced offshore work, either technical or administrative. The sampling strategy was of stratified random where the strata of sampling comprised health and safety practitioners scattered throughout different oil and gas companies in Malaysia (Dahl & Olsen, 2013; Flin et al., 2000).

The managers or designated focal persons in the health and safety department in major oil and gas companies were contacted to facilitate collection of responses. The managers or focal persons expressed their preferences in the mode of survey. If online survey platform was preferred, a link of the questionnaire was sent to the focal persons for dissemination to the relevant staff for their responses. If email method was preferred, emails containing an electronic copy of the questionnaire were sent to the focal persons which were subsequently forwarded to the relevant survey participants. For postal method, printed copies of the survey questionnaires were delivered to the focal persons for dissemination to the survey participants and arrangement was made for collection of the completed questionnaires. Face-to-face data collection was conducted on personal acquaintances working as health and safety professionals in the oil and gas industry.

3.7 Data Analysis

Descriptive statistics comprising mean, variance and standard deviation for importance rating of the indicators and perceived risk due to failure to observe the indicators were generated using the SPSS (IBM, 2014) (refer to Step 6 in **Figure 3.1**). From the mean importance ratings and mean perceived risks of the underpinning indicators, importance of the respective safety factors and the corresponding perceived risk from failure to observe the safety factors were derived as follows:

Importance of safety factor = $\frac{\sum_{i=1}^{n} A_i}{n}$ **(3.2)**

where *A* =Mean importance of corresponding indicators (calculated from the sum of perceived importance ratings of an indicator divided by total responses), and n = Number of corresponding indicators.

Perceived risk due to failure to observe safety factor = $\frac{\sum_{i=1}^{n} P_i}{n}$ **(3.3)**

where *P* = Mean perceived risk due to failure to observe corresponding indicators (calculated from the sum of perceived risk ratings of an indicator divided by total responses), and n = Number of corresponding indicators.

The corresponding variances and standard deviations of safety factors were also generated using SPSS software (IBM, 2014). The importance rating and perceived risk of the safety factors were presented graphically.

Principal component and hierarchical cluster analyses on the perceived importance ratings and the perceived risk ratings were conducted respectively to establish the correlations between the safety factors (Liou et al., 2007; Mulaik, 2010). In principal component analysis, the variables that seemed to share their variance were grouped together (Mulaik, 2010). The threshold of factor loadings was set at 0.40, above which the relationship is considered significant (Morrow et al., 2014). A safety factor with a factor loading of 0.7, therefore, was interpreted as having a correlation of 0.7 to Principal Component 1.

Hierarchical cluster analysis builds a hierarchical cluster via agglomerative method where pairs of safety factors are progressively merged up the hierarchy based on between-group linkage, i.e. the closest smallest average Squared Euclidean distance between the pairs of factors or factor clusters. The pairing of the factors was represented with a dendrogram (University of Northern Texas, 2013). Squared Euclidean distance is expressed as:

$$\sum_{j=1}^{k}(a_j - b_j)^2 \qquad \textbf{(3.4)}$$

where, *a* and *b* are the cases of the j variable to be compared, and k is the total number of variables in the study.

In each agglomerative clustering, clusters or pairs of cases having the smallest Squared Euclidean distance were linked by average linkage (Yim & Ramdeen, 2015). Average linkage calculates the average distance of each case in the first cluster and those of the second cluster, which presents a more accurate way to characterize the distances between two clusters (Yim & Ramdeen, 2015). The formula of average linkage clustering is shown in the following:

$$\frac{1}{|A||B|}\sum_{a\in A}\sum_{b\in B} d(a,b) \qquad \textbf{(3.5)}$$

where A = cluster A, B = cluster B, a = data points of cluster A, b = data points of cluster B, and d = distance between pairs.

Pearson correlations examine how two continuous variables are related based on linear relationship (Eisinga et al., 2013). Pearson correlations between perceived importance and perceived risk ratings of the safety factors were calculated. Pearson coefficient, r, has a range of -1 to +1 with -1 demonstrating an absolute negative correlation, +1 showing an absolute positive correlation and 0 showing absence of correlation. As a rule of thumb, Pearson's r equal to or above +0.5 and below -0.5 shows significantly positive and negative correlations respectively. Pearson's r below +0.5 to +0.3 and above -0.5 to -0.3 shows moderate positive and negative correlations respectively. A Pearson's r ranging from below +0.3 to above –0.3 indicates insignificant correlation (Eisinga et al., 2013). Pearson correlation analysis was also conducted on the mean perceived importance ratings of the safety factors to confirm the correlations established via principal component and hierarchical analyses established earlier on.

3.8 Establishment of Safety Performance Measurement Framework

Subsequent to analysis of the safety indicators and safety factors, a safety performance measurement framework was established to evaluate the safety performance of offshore oil and gas platforms. An overview of this phase of study is shown in **Figure 3.5**. The set-up of the framework is shown in **Figure 3.6**.

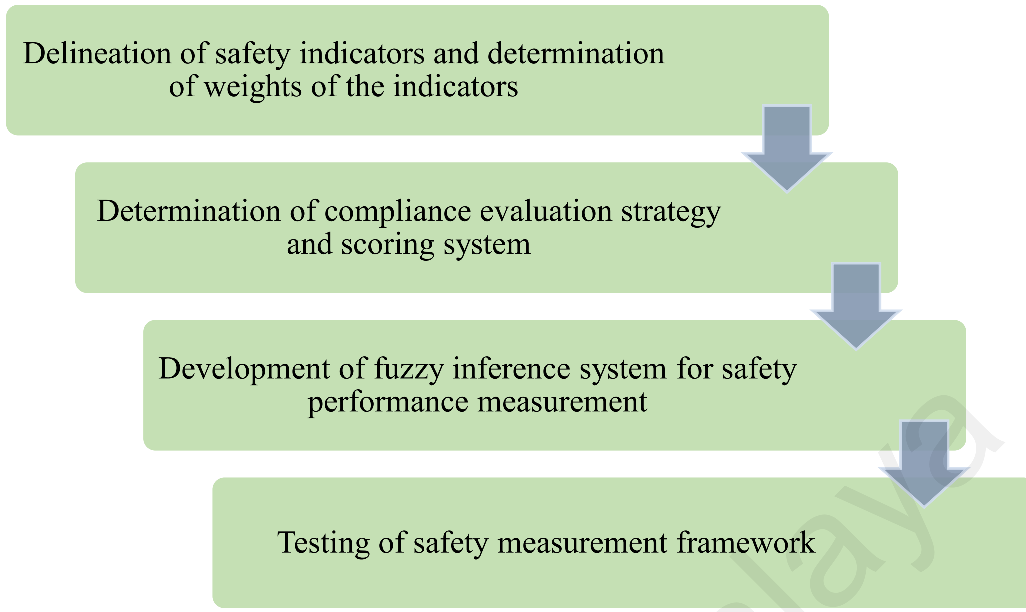


Figure 3.5: Procedures for Establishment of Safety Performance Measurement Framework

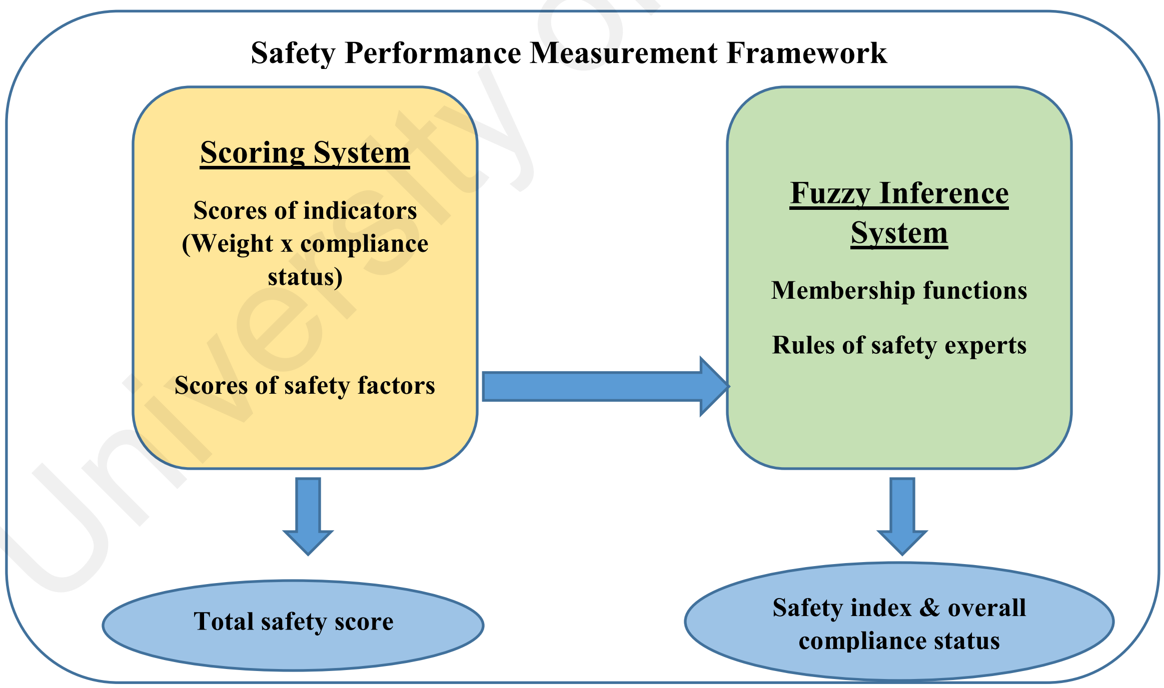


Figure 3.6: Architecture of the Safety Performance Measurement Framework

3.8.1 Delineation of Safety Indicators and Determination of Weights of the Indicators

The safety indicators underwent a final round of review by the industrial practitioners to ensure better relevance and clarity as well as to decrease redundancy. Some indicators with inadequate relevance and clarity, as well as some having lowest weights within the corresponding safety factors were removed, yielding a total of 63 final indicators grouped under 14 safety factors for the safety performance measurement framework. The modified and omitted indicators and the reasons of modification and omission are shown in **Appendix C**.

Common methods of weight determination include equal weights which assume all indicators have the same importance, weights based on statistical models where lower weights are assigned to correlated indicators measuring a particular domain to avoid double counting as correlated indicators may provide overlapping information, as well as weights based on public/ expert opinion (Jacobs et al., 2004; Ravana & Moffat, 2009). Weights based on public/ expert opinion was adopted in this study as the survey was conducted among the health and safety practitioners of oil and gas companies in Malaysia.

The weight of each indicator was generated in a straightforward manner by multiplying the mean importance rating and mean perceived risk rating for each indicator. This is similar to risk scoring by multiplying perceived severity of a hazard with the perceived probability of its occurrence and has been indicated in the literature as a potential strategy of weight determination (Rundmo, 1992; Øien & Sklet, 1999; Øien et al., 2010) where perceived risk was taken into account for deriving weights of risk-based and organizational risk indicators.

3.8.2 Determination of Compliance Evaluation Strategy and Scoring System

As part of safety performance measurement, a strategy to determine compliance of the safety indicators was discussed in consultation with the industrial practitioners. It was generally agreed that the traffic light system proposed by the HSE (2008) in its Asset Integrity Key Program could be adopted for compliance determination where red indicates non-compliance, amber indicates isolated failure or incomplete system and green indicates compliance. Adaptation was made to permit generation of numerical data for scoring of safety performance. The adaptation involved assigning a number instead of a color to the compliance status where “3” was assigned for compliance, “2” for isolated failure or incomplete system and “1” for non-compliance. It was highlighted that safety data collected may vary between platforms of different oil and gas companies and may not address all the indicators recommended (HSE, 2008). As such, “0” was assigned to critical indicators without data collected. Assignment of the compliance status score is commonly conducted by health and safety experts based on the targets or performance standards set for the respective safety indicators, and is highly dependent on experts’ judgement as well as clarity of performance standards. It is noteworthy that performance measurement compares actual performance against performance targets or standards set by the higher management in line with corporate goals and external factors such as legislations and competition (Bhandari & Azevedo, 2013).

With the weights determined and compliance determination strategy framed, compliance score of each safety factor can be calculated via aggregation of scores of individual indicators. A safety factor socre is calculated by additive aggregation method which involves adding the product of weight and compliance status score of each indicator grouped under the safety factor. Additive aggregation method is most widely used in calculation of composite score, for instance environmental sustainability index and takes into consideration marginal contribution of each indicator to the total performance (Jacobs et al., 2004; Ravana & Moffat, 2009). The formula for additive aggregation is shown below:

$$SF_j = \sum_{i=1}^{m} y_{ij}\, w_{ij} \qquad \textbf{(3.6)}$$

where SF_j = score of safety factor j, y_{ij} = compliance score of i^{th} indicator classified under safety factor j, and w_{ij} = weight of i^{th} indicator under safety factor j.

The equation shows that the total score of safety factor j can be calculated by summing the products of *m* respective indicators under the safety factor and their respective weights (Ravana & Moffat, 2009).

The total safety score of a platform can then be calculated by summing the individual safety scores as below:

$$TS = \sum_{i=1}^{14} SF_i \qquad \textbf{(3.7)}$$

where TS = Total Safety Score of a platform, and SF = Score of i^{th} safety factor.

3.8.3 Development of Fuzzy Inference System for Safety Performance Measurement

Fuzzy inference system has been integrated to the framework whose inputs and outputs are also associated with linguistic variables in addition to scores. Four steps consisting of fuzzification, defuzzification, determination of rules and fuzzy inference are involved in the establishment of a fuzzy inference system.

3.8.3.1 Data Fuzzification

Fuzzy logics solve problems related to uncertainty, ambiguity and imprecision between input variables and outputs variables by giving definite answers to vague questions through fuzzified inputs.

In this study, the linguistic variables comprise the various degrees of compliance, i.e. compliance, deviated and non-compliance. The linguistic variables are defined by the respective granular variables dictating the range of values associated with the linguistic variables, for example, the linguistic variable 'compliance' consists of all values above 75 for the safety factor of inspection and maintenance (refer **Figure 3.7**). Therefore, a singular value of, say 80, falls within the granular variable which is associated with 'compliance' linguistically.

Figure 3.7: Triangular Membership Function for Input Variable 'Inspection and Maintenance' (also referred to as Scenario A)

Membership function of the fuzzy logic expresses how a singular or point value is related to the degree of membership between 0 and 1. The degree of membership is associated with the possibility of fuzzy set having partial membership, for instance a safety factor is almost compliant or is rather deviated. Triangular and trapezoidal types of fuzzy set membership functions are most commonly used (Bandemer & Gottwald, 1995; Azadeh et al., 2008) and have the advantage of simplicity.

Both the membership functions were tested and compared in this study. Triangular membership function is defined by a lower limit **a**, an upper limit **b**, and a value **m** corresponding to the membership function value of 1, i.e. $\mu A(x) = 1$, as shown in **Equation 3.8**.

$$\mu A(x) = \begin{cases} 0 & x \leq a \\ \frac{x-a}{m-a} & a < x \leq m \\ \frac{b-x}{b-m} & f < x < b \\ 0 & x \geq b \end{cases} \quad \textbf{(3.8)}$$

The triangular membership function peaks at the maximum possible score for each state of compliance. **Figure 3.7** shows that maximum score for a state of 'compliant' is 115, that for a 'deviated' state is 76 and that for a 'non-compliant state' is 0. The maximum scores therefore correspond to the highest membership degree. The degree of one membership function decreases while the degree of another membership function increases in a linear manner.

Unlike triangular membership function, trapezoidal membership function has an upper support limit, **c** and a lower support limit **b**, as shown in **Equation 3.9**, **Table 3.2** (Bandemer & Gottwald, 1995). These limits can be seen for the 'deviated' status in **Figure 3.8**. The upper and lower support limits demonstrate a tolerance range of safety scores that can be considered totally deviated with $\mu A(x) = 1$. The degree of 'deviation' decreases above and below the support limits, as shown in **Figure 3.8**. The 'non-compliant' status is defined by R-function of trapezoidal type membership function where the lower limit is equal to the lower support limit (**Equation 3.10**, **Table 3.2**). The 'compliant' status is defined by L-function of trapezoidal type membership function with the upper limit equal to the upper support limit (**Equation 3.11**, **Table 3.2**).

Table 3.2: Mathematical Representation of Trapezoidal Membership Function (Klir & Yuan, 1995)

Membership Function Type	Mathematical Representation
Trapezoidal	$\mu A(x) = \begin{cases} 0 \;\; (x < a) \; or \; (x > d) & \\ \frac{x-a}{b-a} & a \le x \le b \\ 1 & b \le x \le c \\ \frac{d-x}{d-c} & c \le x \le d \end{cases}$ **(3.9)**
R-function	$\mu A(x) = \begin{cases} 0 & x > d \\ \frac{d-x}{d-c} & c \le x \le d \\ 1 & x < c \end{cases}$ **(3.10)**
L-function	$\mu A(x) = \begin{cases} 0 & x < a \\ \frac{x-a}{b-a} & a \le x \le b \\ 1 & x > b \end{cases}$ **(3.11)**

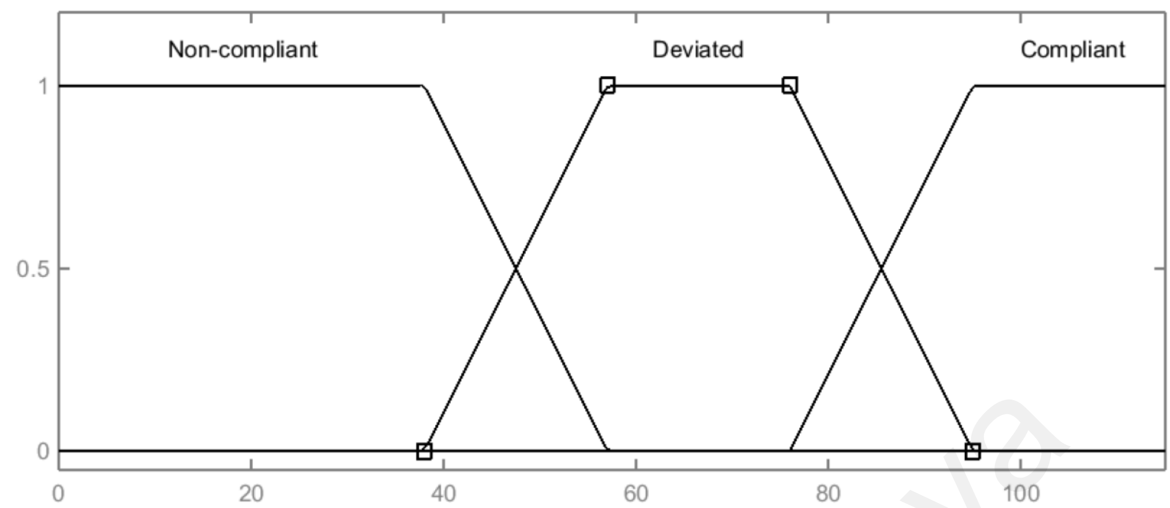


Figure 3.8: Trapezoidal Membership Function for Input Variable 'Inspection and Maintenance' (also referred to as Scenario B)

The use of trapezoidal membership function involves an additional step of determining the two additional limits (Bandemer & Gottwald, 1995). In this scenario, for the 'deviated' membership function, the upper limit is the average of the maximum scores of 'compliant' and 'deviated' states while the maximum score of 'deviated' state is taken as the upper support limit. This means that safety score is considered fully compliant once it hits the upper limit, unlike the triangular membership function where full compliance is only attained at the maximum score. The lower support limit of the 'deviated' membership function is taken as the average of the maximum scores of 'deviated' and 'non-compliant' states whereas the lower limit is the maximum score of 'non-compliant' state. Mathematical representation of the trapezoidal type membership functions is shown in **Table 3.2**.

The input variable is considered compliant if the score of the safety factor meets or exceeds the targets or the performance standards. This is, in turn, determined from the compliance status of the individual indicators underpinning the respective safety factors. For

‘Inspection and Maintenance’ shown in **Figure 3.8**, a status of full non-compliance is denoted by χ <38. 38 represents the total score obtained when all indicators under the safety factor are non-compliant, calculated based on **Equation 3.6**. For a non-compliant status, the compliance score assigned to an indicator is ‘1’. By the same method of calculation, the score of deviation is denoted by $38 \leq \chi \leq 95$ while compliance is denoted by a score of $\chi > 95$. Deviation state is represented by a range of score between fully non-compliance and fully compliance as indicated by **Figure 3.8**.

It is also common to combine both triangular and trapezoidal membership functions for an input variable to enable better characterization of the linguistic values (Gerla, 2001). A third scenario presents the use of both membership functions for a single input variable (**Figure 3.9**). Trapezoidal membership function is used for ‘non-compliant’ state assuming that total ‘non-compliant’ is achieved when the input variable has a score of 38. This means all the underlying indicators have a state of ‘non-compliant’, with a compliance score of ‘1’ assigned. Though a lower safety score is possible due to absence of data, especially if the indicator is not adopted, this scenario does not attempt to make a distinction of the membership degree in relation to scores lower than 38.

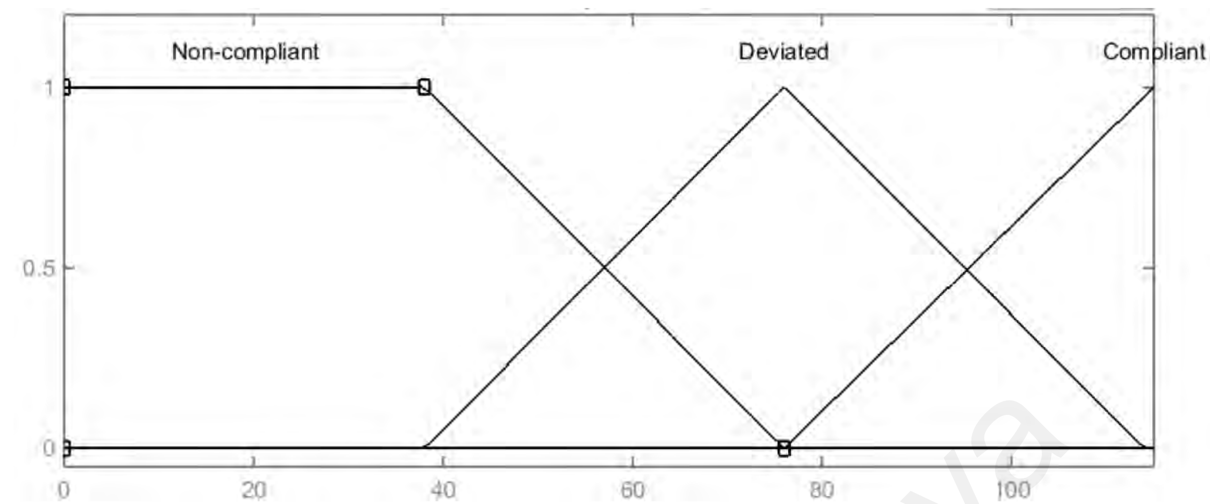


Figure 3.9: Trapezoidal and Triangular Membership Functions for Input Variable 'Inspection and Maintenance' (also referred to as Scenario C)

3.8.3.2 Data Defuzzification

In data defuzzification, numerical result is produced from linguistic variables. Common methods of defuzzification are center of area, center of sum, maximum center average, mean of maximum, smallest of maximum and largest of maximum, with center of area being the most widely used (Bandemer & Gottwald, 1995). The fuzzy inference system adopts center of area defuzzification as suggested by few previous studies on development of fuzzy inference system for similar purpose (Verma & Zakos, 2001; Kwong et al., 2002; Azadeh et al., 2008; Sa'idi et al., 2014). The Center of Area defuzzification consists of two steps, i.e. calculation of area bounded by the scaled membership functions within the output variable range, followed by calculation of geometric center of the area using the equation shown below (Zadeh, 2008; Gerla, 2001).

$$CoA = \frac{\int_{X_{min}}^{X_{max}} \mu(x).x\text{dx}}{\int_{X_{min}}^{X_{max}} \mu(x)\text{dx}} \qquad \textbf{(3.12)}$$

where CoA = fuzzy output from centre of area, x = value of the linguistic variable with x_{min} and x_{max} being the variable range, and u(x) = the membership function.

The full area under the scaled membership functions, as shown in **Figure 3.10**, is calculated by integration of the membership function in the specified range of linguistic variable values using **Equation 3.12**.

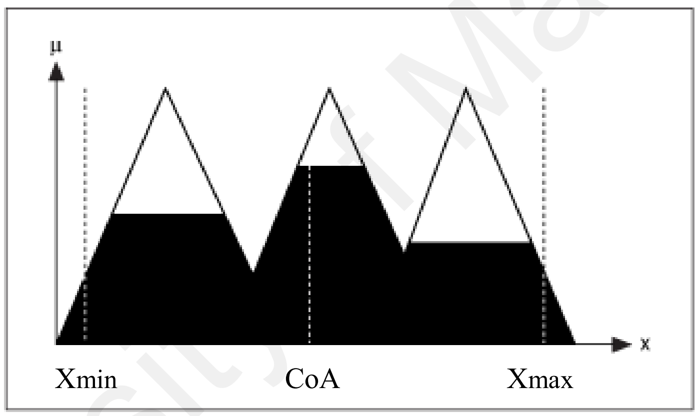


Figure 3.10: Diagrammatic Illustration of CoA Defuzzification (National Instruments, 2010)

For comparison, the mean of maximum (MoM) was tested for the fuzzy inference system with membership function scenario C (**Figure 3.9**). As with CoA, MoM is most frequently used to generate outputs of crisp controllers. MoM computes the mean of x values where the fuzzy output membership function is maximized (Saade & Diab, 2004). The equation for mean of maxima is shown below. Diagrammatic representation of mean of maxima is shown in **Figure 3.11.**

$$MoM = \frac{\int_{Xmin}^{Xmax} x dx}{\int_{Xmin}^{Xmax} dx} \quad \textbf{(3.13)}$$

where MoM = fuzzy output from mean of maxima, and x = value of the linguistic variable, ranging from *Xmax* to *Xmin* at which the fuzzy output is maximized.

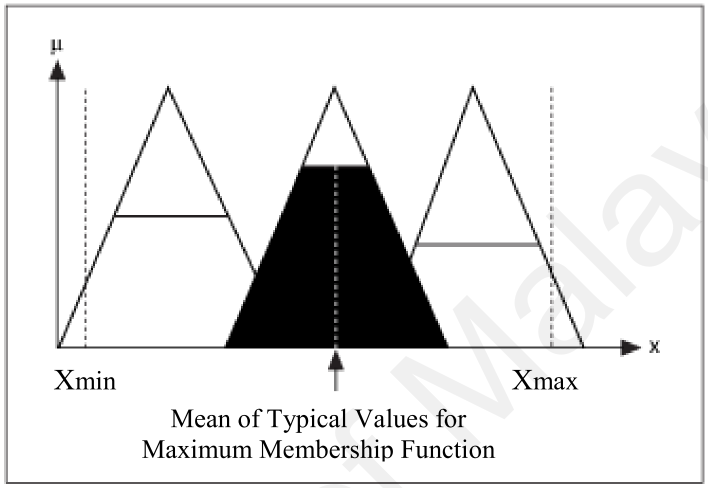


Figure 3.11: Diagrammatic Illustration of MoM Defuzzification (National Instruments, 2010)

3.8.3.3 Determining Rules

Compliance score for each safety factor was calculated as **Equation 3.6, Section 3.8.2**. Using scores of the safety factors as inputs, the fuzzy inference system then determined the safety performance of the offshore oil and gas platform based on a set of rules contributed via consultation with the health and safety practitioners. The rules were framed in the format of 'If… then…" as shown below:

IF inspection and maintenance is compliant,

AND emergency management is compliant,

AND management and work engagement on safety is compliant, AND number of incidents is compliant,

AND personal safety is compliant,

AND contractors' safety is compliant,

AND management of change is compliant,

AND operation and operating procedures is compliant,

AND competence is compliant,

AND hazard identification and risk assessment is compliant,

AND plant design is compliant,

AND instrumentation and alarm is compliant,

AND documentation is compliant,

AND start-ups and shutdown is compliant,

THEN safety performance is compliant

Safety performance is the output of the fuzzy inference system where four levels/ states were identified, i.e. compliant, slightly deviated, highly deviated and non-compliant (**Figure 3.12**). Two levels of deviation were defined in order that severity of deviation can be captured to prompt appropriate response (Azadeh et al., 2008). **Figure 3.12** depicts overlapping membership functions which show an inverse relation between the states of compliance, i.e. as the degree of one state of compliance increases, the degree of another state decreases proportionally. Alternatively, the membership functions dictating the levels/ states of compliance can be non-overlapping as shown in **Figure 3.13**, thus, indicating a lack of inter-relation between the states.

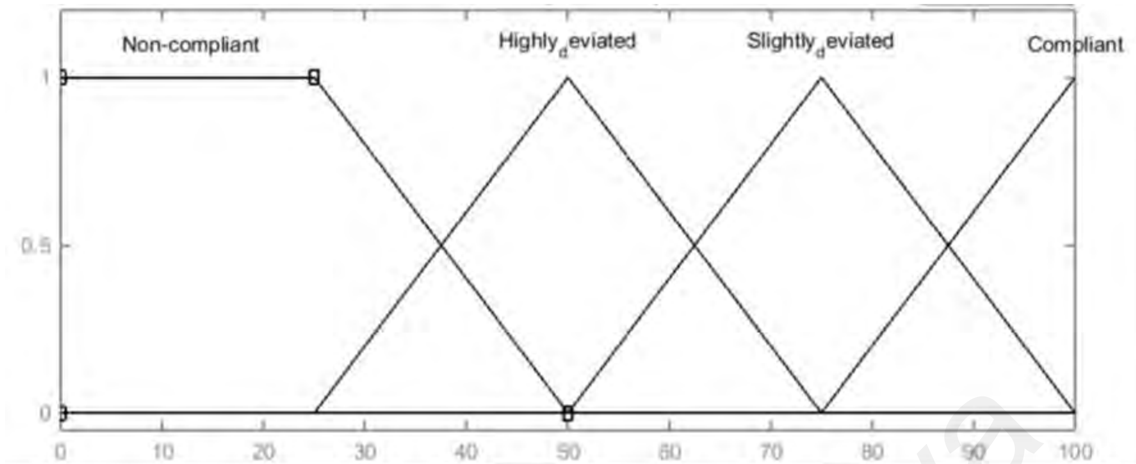


Figure 3.12: Overlapping Membership Functions for the Output of Fuzzy Inference System

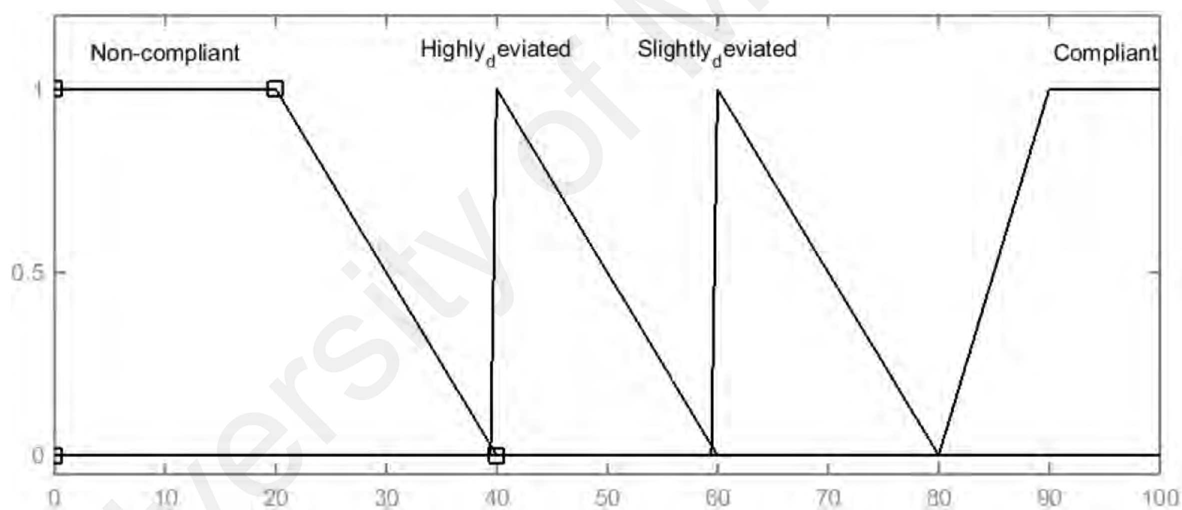


Figure 3.13: Non-overlapping Membership Functions for the Output of Fuzzy Inference System

50 rules were entered into the system based on the simplistic rule combinations generally agreed by the industrial practitioners consulted, as shown in **Table 3.3**. The rules were determined in a qualitative manner based on what the practitioners deemed were appropriate to be considered compliant, slightly deviated, highly deviated and non-compliant in relation

to the safety performance of offshore oil and gas platforms. The rules do not capture all possible scenarios and are subject to improvement as experience in this area grows. Due to a lack of an integrative approach for safety management in the Malaysian offshore oil and gas platforms, assigning an overall safety status to the platforms is not currently practiced and rule-setting to determine safety status is itself a new experience to the practitioners.

Table 3.3: Combination of Rules based on Expert Opinion

For a safety system to be considered:	**Number of safety factors with the following state:**		
	Deviated	**And/ Or**	**Non-compliant**
Compliant	0	And	0
	1	And	0
	2	And	0
Slightly Deviated	0	And	1
	0	And	2
	1	And	1
	2	And	1
	1	And	2
	3	And	1
	4	And	0
Highly Deviated	2	And	2
	1	And	3
	4	And	1
	3	And	2
	2	And	3
	1	And	4
	4	And	2
	3	And	3
	2	And	4
	1	And	5
Non-compliant	>10	Or	>7

3.8.3.4 Fuzzy Inference

Fuzzy inference employs aggregation operator to combine the outputs for each rule into a single fuzzy set. Aggregation operator determines if the rules are fulfilled based on their initial conditions (Azadeh et al., 2015). MATLAB Fuzzy Logic Designer was used to create the fuzzy inference system (MathWorks, 2017). The output of the fuzzy inference system consists of four states, i.e. compliant, slightly deviated, highly deviated and non-compliant as also mentioned in the previous section (refer **Figure 3.12**). **Figure 3.13** shows a different output with non-overlapping membership functions.

3.8.3.5 Alternative Set-Up of Fuzzy Inference System

Inter-related safety factors were combined based on their perceived importance as demonstrated by factor analysis and hierarchical cluster analysis (**Section 3.7**) to form intermediate fuzzy models which then feed into an integration model. The hierarchical clustering of perceived importance is shown in **Figure 4.5** of **Chaper 4**. The set-up is shown in **Figure 3.14** below is different from an unpartitioned design as shown in **Figure 3.15** typical of a fuzzy inference system. While scores of the safety factor serve as inputs of both designs, the unpartitioned design does not produce intermediate scores as with the alternative design.

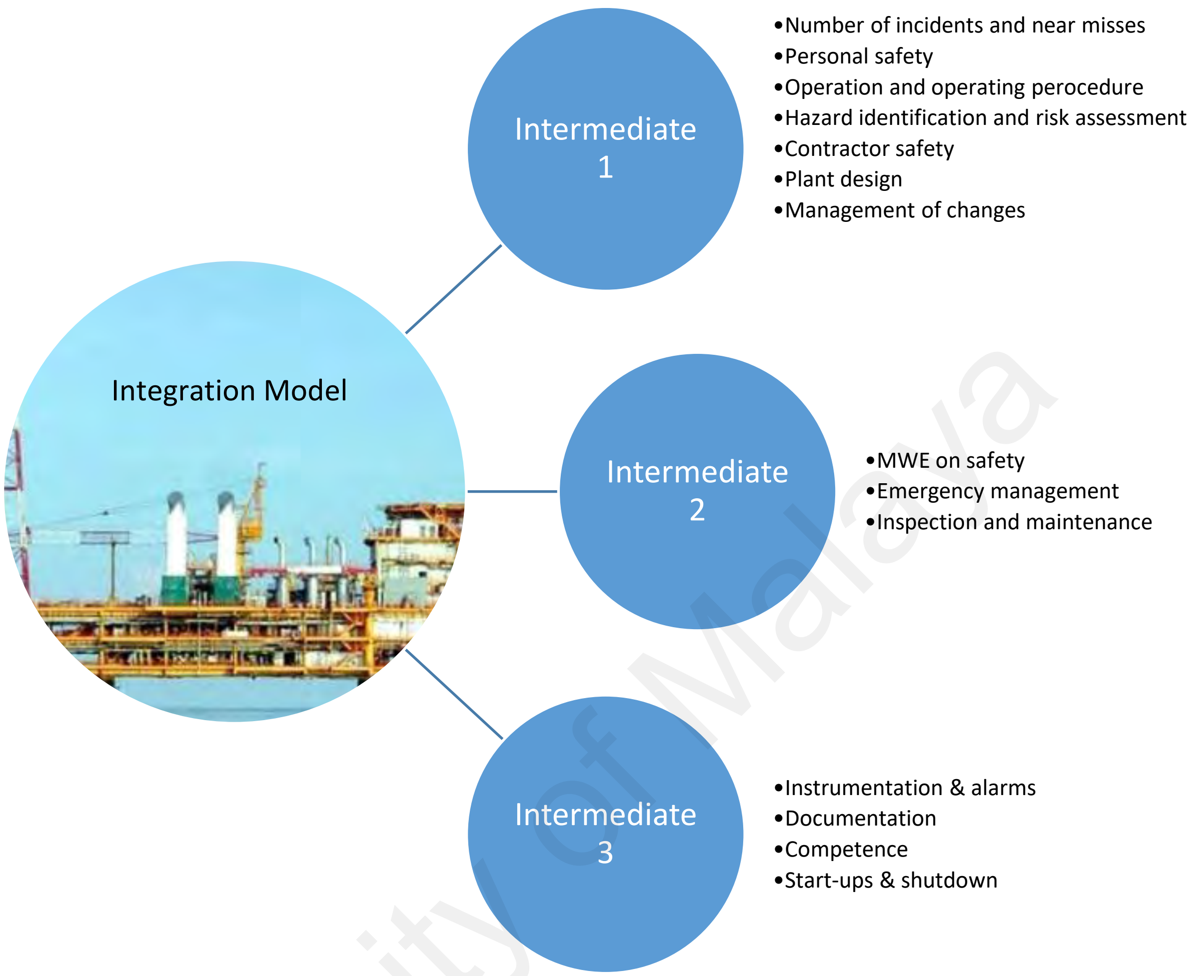


Figure 3.14: Alternative Set-up of Fuzzy Inference System for Safety Performance Measurement

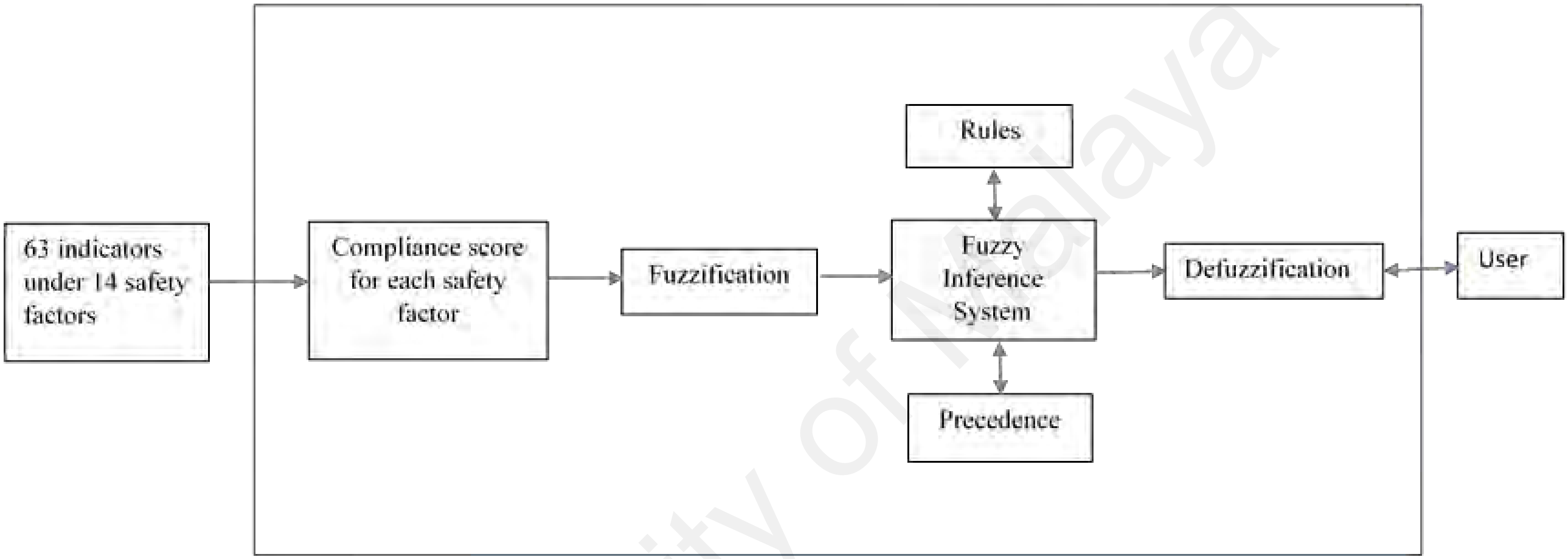


Figure 3.15: Fuzzy Inference System for Safety Performance Evaluation without Intermediate Models

Trapezoidal and triangular membership function senario (Scenario C, also refer **Figure 3.9**) was selected based on the rationale that it has the highest R-squared value for a plot of crisp value against safety score [refer **Figure 4.18(a)**, **Chapter 4**] and it best describes the various compliance status, according to the industrial practitioners. Membership functions of the intermediate outputs are shown in **Figure 3.16**. Two designs of intermediate outputs, i.e. one with larger extent of overlapping between the membership functions and another with no overlapping between the membership functions, as shown in **Figures 3.17** and **3.18** were also tested.

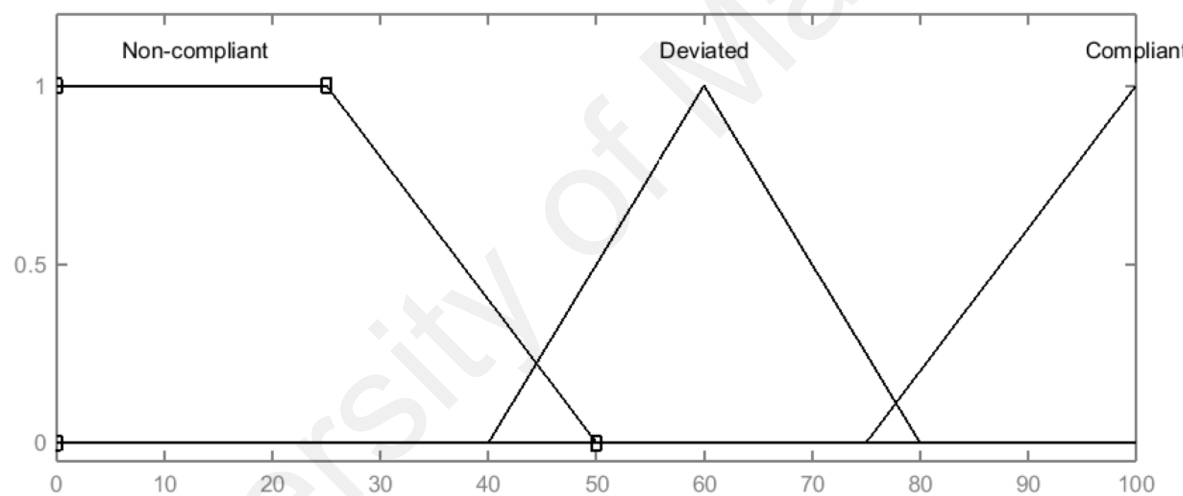


Figure 3.16: Membership Functions with Low Overlapping for Intermediate Outputs

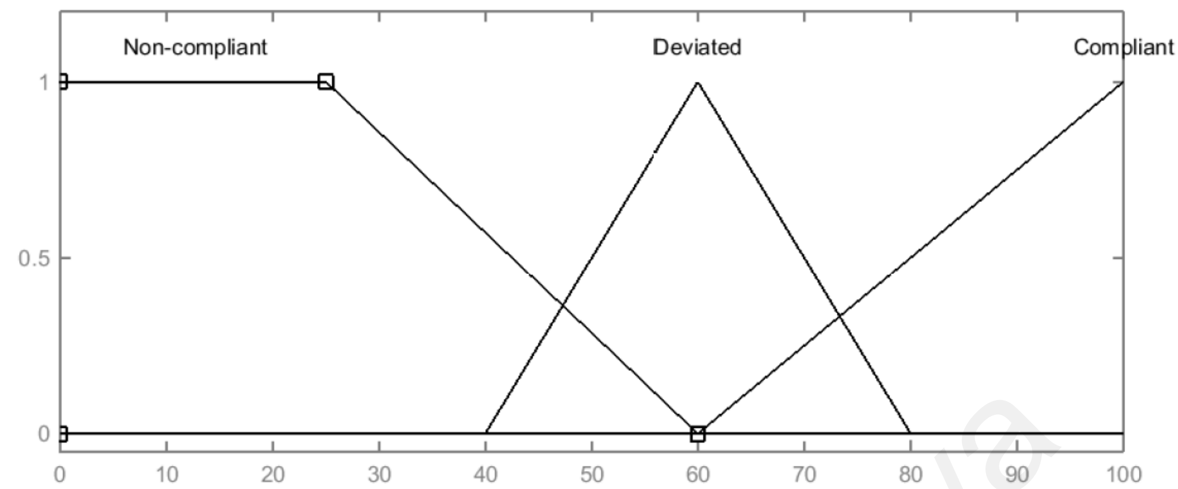


Figure 3.17: Membership Functions with High Overlapping for Intermediate Outputs

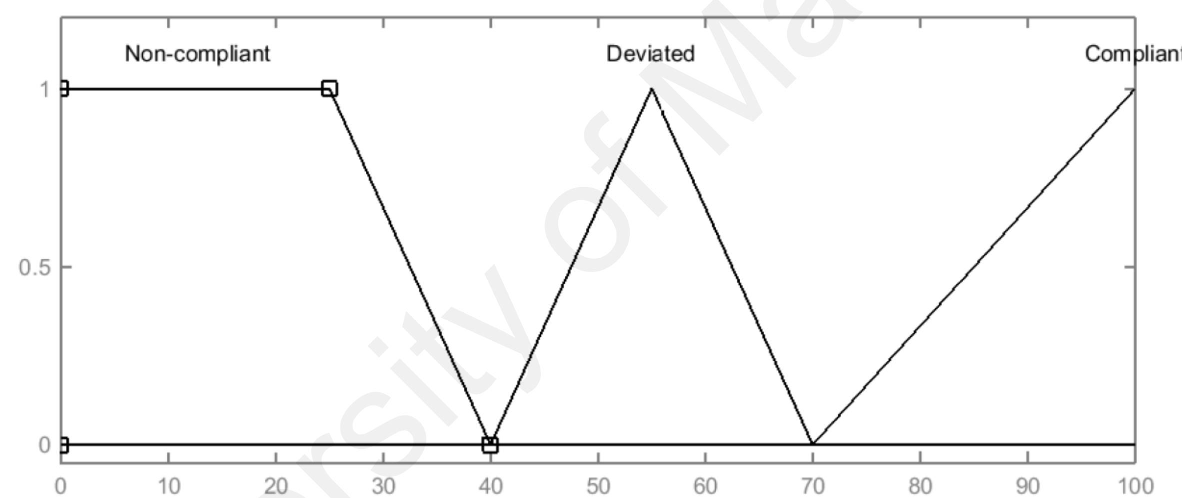


Figure 3.18: Non-overlapping Membership Functions for Intermediate Outputs

Three states of compliance were defined for the intermediate models to simplify rules making. **Figure 3.16** shows that a facility with a score of 75 and above has increasing state of compliance. With a score of 50 and below, non-compliance is increasing to the point where all indicators assume non-compliance status. The plateau from 0 to 25 represents situation where lower scores could be possible due to the absence of indicators or mechanism to collect data for indicators. **Figure 3.17** shows a larger degree of overlapping between the membership functions where the degree of membership of the 'deviated' state decreases with increasing degree of membership of the 'compliant' state and the 'non-compliant' state respectively at 60. **Figure 3.18** indicates three ranges of non-overlapping scores for compliant, deviated and non-compliant respectively.

The intermediate outputs feed to the integration model with the same output membership functions as shown in **Figure 3.12**. Rule-setting for the intermediate and integration models was qualitatively conducted based on the perceived importance of the safety factors, with reference made to the survey findings in **Section 3.7**, in contrast to **Table 3.3** which was based entirely on numbers of compliance, deviation and non-compliance. Examples of rule set for the alternative set-up are shown in **Table 3.4** below.

Table 3.4: Example of Rules for Alternative Fuzzy Inference System Set-up

Entity	**Example of Rules**
Intermediate 1	If number of incident and near misses is deviated; and personal safety is compliant; and operation and operating procedures is compliant; and hazard identification and risk assessment is compliant; contractor safety is compliant; plant design is compliant; and change management is compliant, then Intermediate 1 is compliant If number of incident and near misses is compliant; and personal safety is non-compliant; and operation and operating procedures is compliant; and hazard identification and risk assessment is compliant; contractor safety is compliant; plant design is compliant; and change management is compliant, then Intermediate 1 is deviated
Intermediate 2	If MWE on safety is compliant; and emergency management is deviated; and inspection & maintenance is compliant, then Intermediate 2 is deviated If MWE on safety is compliant; and emergency management is compliant and inspection & maintenance is deviated, then Intermediate 2 is compliant
Intermediate 3	If instrumentation and alarm is compliant; and documentation is compliant; and competence is compliant; and start-ups and shutdown is compliant, then Intermediate 3 is compliant

Entity	Example of Rules
	If instrumentation and alarm is compliant; and documentation is compliant; and competence is compliant; and start-ups and shutdown is deviated, then Intermediate 3 is deviated
Final Integrated Model	If Intermediate 1 is compliant; and Intermediate 2 is compliant; and Intermediate 3 is compliant, then Platform Safety Performance is compliant If Intermediate 1 is compliant; and Intermediate 2 is deviated; and Intermediate 3 is compliant, then Platform Safety Performance is slightly deviated If Intermediate 1 is compliant; and Intermediate 2 is deviated; and Intermediate 3 is deviated, then Platform Safety Performance is highly deviated

3.9 System Testing

3.9.1 Sensitivity Analysis

Sensitivity analysis was conducted to examine how 10 indicators with the highest weights and 10 indicators with the lowest weights affect the total safety score respectively by altering the compliance states of the indicators while keeping the compliance state of the remaining indicators constant. The analysis was repeated with 20 indicators having the highest weights and the lowest weights respectively.

To establish the sensitivity of the weights, sensitivity analysis was repeated with weights based on perceived importance and perceived risk respectively, in addition to the products of perceived importance and perceived risk used above.

Sensitivity was also represented with sensitivity index calculated as following (Pannell, 1997):

$$SI = (D_{max} - D_{min}) / D_{max} \qquad \textbf{(3.14)}$$

where SI = Sensitivity index, D_{max} = output when parameter of interest is at its maximum value, and D_{min} = output when parameter of interest is at its minimum value

3.9.2 Testing of Safety Performance Measurement Framework

Predictive ability of the safety performance measurement framework was tested by drawing a correlation between the actual performance of 10 offshore oil platforms and the evaluated safety performance of the platforms using the framework proposed. Selection of platforms was entirely based on these criteria 1) data availability, as the release of data depended entirely on the discretion of the industrial practitioners though specific requests were communicated, 2) the offshore platforms must produce oil or gas, or both; the data were subject to geographical constraints of the study participants which were based in Miri and the offshore platforms in Miri were mostly oil-producing platforms, 3) the offshore platforms must be manned, and in the waters of Miri, the manned platforms were primarily fixed platforms.

Fundamentally, there is no difference between the drilling for oil and gas as most oil wells produce some natural gas and vice versa. Therefore, an oil platform and a gas platform do not differ significantly (Chia et al., 2003). The actual performance centered around the number of fatality, fatal accident rate, total recordable incident rate, lost time injury rate and reported near-misses in year 2016.

A questionnaire consisting of a final list of 63 safety indicators grouped under 14 safety factors as mentioned earlier (**Table 3.1** shows the safety factors), as well as a section for actual performance reporting with the parameters mentioned above (refer **Appendix D** for testing questionnaire) were disseminated to the participating industrial practitioners in three oil and gas companies in Malaysia. The industrial practitioners involved in collection of safety performance data for safety reporting and were best-suited to provide data for the questionnaire. Descriptive statistics including range, means, standard deviation and variance were calculated for each factor to give an overview of how the performance of each safety factor varied among the platforms. Correlation between the scores of safety factors and the actual performance of the offshore oil and gas platforms was analyzed using Pearson correlation (IBM, 2014). **Figure 3.19** provides an overview of the safety performance measurement framework.

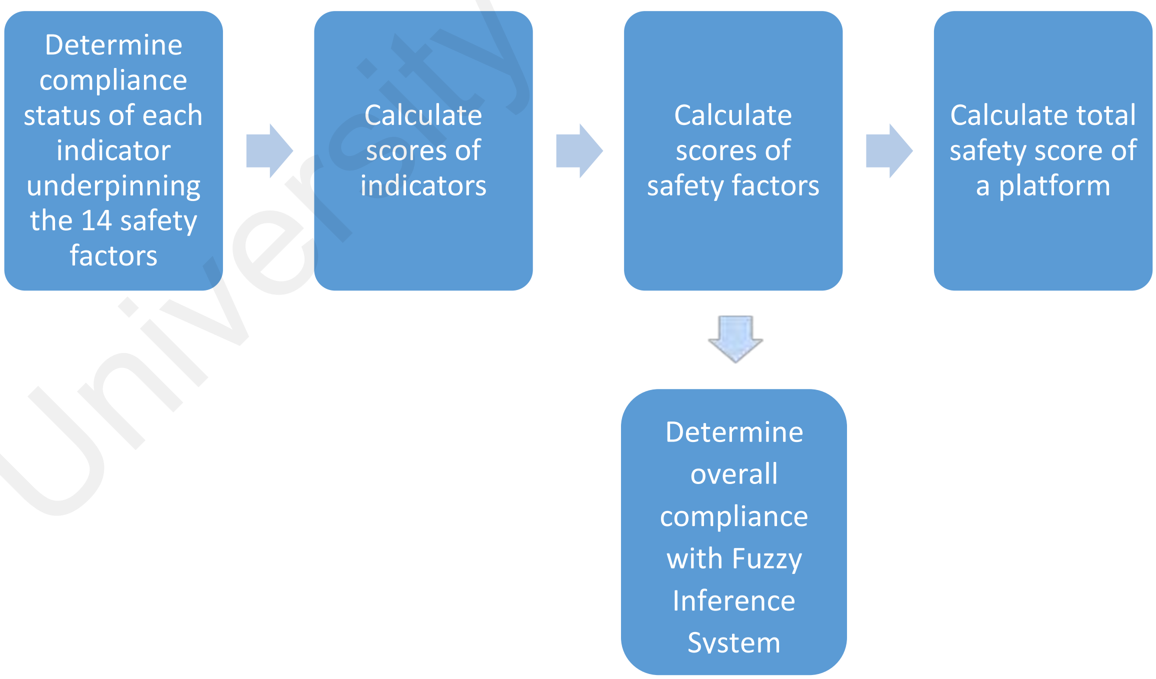


Figure 3.19: Safety Performance Measurement

3.9.3 Testing of Fuzzy Inference System

The fuzzy inference system was tested on the safety performance data of the 10 platforms mentioned and 15 safety performance scenarios, with the 3 respective membership functions mentioned, i.e. triangular, trapezoidal as well as triangular and trapezoidal combined, to determine the respective overall compliance status and generate the corresponding composite safety index. Testing of the alternative set-up of fuzzy inference system with intermediate models was also conducted. Crisp outputs generated from various scenarios were compared in terms of their changes against the total safety scores. In this case, the R-squared value was used for comparison.

3.9.4 Validation of the Safety Performance Measurement Framework

The safety performance measurement framework was validated against the facility status reporting of groups of safety critical elements (SCE), of two offshore oil platforms in Miri, Malaysia, located at a water depth of approximately 90m. Facility status reporting of oil and gas platform using the SCE was promulgated by HSE's Key Programme 3 (KP3) to ensure platform operators manage risk related to structure, plant and equipment effectively in the prevention of major accidents and report performance of SCE in standardized format, thus facilitating sharing of best practices and benchmarking (HSE, 2008).

Facility status reporting is part of safety performance measurement currently practiced on offshore oil and gas platforms and bears much resemblance to the proposed framework, particularly in indicating the compliance status of each SCE. The reporting system employs the traffic light method recommended by the HSE with red indicating non-compliance, amber indicating isolated failure or incomplete system and green indicating compliance (Frens &

Berg, 2014). In Malaysia, facility status report is not readily accessible and its use is subject to confidentiality policy of the providing company.

The safety score and status obtained from the proposed framework is compared against the findings of facility status reporting of an oil platform in Malaysia to examine how close the findings from both instruments are in terms of the platform safety performance.

CHAPTER 4: RESULTS AND ANALYSIS

4.1 Overview

The chapter begins with profiles of oil and gas companies from which responses were collected and the profiles of respondents. It presents the Cronbach's alpha which indicates the reliability of the survey items, hence the safety factors. It then demonstrates the descriptive statistics of the perceived importance ratings and perceived risk ratings (due to failure to observe the indicators), particularly the means, variances and standard deviations. This chapter goes on to show the findings of correlation analysis of perceived importance ratings and perceived risk ratings of the safety factors respectively, consisting of factor analysis, hierarchical clustering and Pearson correlations.

This chapter also outlines the safety performance measurement scoring system and highlights the results of its sensitivity analysis via alterations of compliance states of indicators, as well as weights of indicators. In the sensitivity analysis, the weights solely from mean perceived importance and mean perceived risk respectively, as well as those from multiplications of mean perceived importance and mean perceived risk were compared. Subsequently, results associated with testing of the fuzzy inference system as part of the safety performance measurement framework to confer a final state of compliance and generate a safety index for safety performance of offshore oil and gas platforms are presented. The testing involved two set-ups of fuzzy inference system, one with intermediate models and one without. The testing was based on actual safety performance of 10 offshore oil platforms as well as 15 safety performance scenarios.

Lastly, this chapter reveals how the framework performs in comparison to an existing safety performance evaluation practice of the offshore oil and gas platforms.

4.2 Profile of Respondents and Cronbach's Alpha

To leverage on the experiences of industrial practitioners in determining the most pertinent safety indicators for safety performance measurement of offshore oil and gas installations in Malaysia, survey questionnaire was used to gather the data on perceived importance of the safety indicators and perceived risk of failing to observe or implement the indicators. The responses were collected from ten (10) major oil and gas companies involving either directly in offshore oil and gas exploration and production or those providing engineering and drilling services to the oil and gas companies. Below is a brief overview of the companies.

1. Dayang Enterprise, a service provider to oil and gas companies encompassing maintenance, fabrication as well as hook-up and commissioning.
2. JX Nippon Oil & Gas Exploration Corporation, an entity of the JXTG Group headquartered in Japan which focuses on development and production of oil and natural gas.
3. MMC Oil and Gas Engineering Sdn Bhd, a subsidiary of MMC Corporation Bhd which provides engineering, procurement, construction and commissioning services to oil and gas companies.
4. Murphy Oil Corporation, a North American oil and gas company which entered Malaysia in 1999 and contributed approximately 35% of total net production as of 2016.
5. Petronas Carigali Sdn Bhd, a subsidiary of Petronas, a Malaysia-based multinational oil and gas corporation, which is involved in oil and gas exploration and production.
6. Punj Lloyd Oil and Gas Malaysia Sdn Bhd, a company which provides services in onshore and offshore field development in addition to producing and supplying oil and gas products.

7. ROC Oil, an Australian upstream oil and gas company which holds 30% interest in the production sharing contract of D35/D21/J4 offshore Sarawak.
8. Schlumberger (Malaysia) Sdn Bhd, a company which provides reservoir characterization, drilling, production and processing technologies to oil and gas companies.
9. Shell Malaysia, including Sarawak Shell Berhad, a subsidiary of Royal Dutch Shell which conducts oil and gas exploration and production.
10. UMW Oil and Gas Corporation Berhad, a subsidiary of UMW Group which offers mainly drilling and oilfield services to upstream oil and gas activities.

A total of 187 questionnaires were returned. The questionnaires were screened for completeness of responses. Only 172 questionnaires were complete and qualified for subsequent analyses. There is no official record of the total number of health and safety personnel employed in the oil and gas sector in Malaysia. Statistical record of the Department of Occupational Safety and health Malaysia showed a total of 5984 registered safety officers in Malaysia as of 2016 and more than half of them were inactive or had expired licenses. In 2014, the oil and gas sector employed a total of 17350 staff (Department of Statistics, 2017). With reasonable approximation that 10% of the staff were health and safety practitioners (Petronas, 2015), the number of respondents in this study was deemed sufficient. According to Yamane (1992), for a population size of 2000, to achieve a precision level of ±10% with confidence level of 95%, the required sample size is only 95.

The profiles of responses and respondents are shown in **Table 4.1** and **Table 4.2** respectively. As the respondents were not provided with categories of job areas and positions in the survey questionnaire, the job areas and positions were deduced from the job titles provided by the respondents in the completed questionnaires. General health and safety includes respondents whose work revolves around health and safety even though the job scope may cover quality aspects (**Table 4.2**). Their jobs centered on management of occupational or personal safety including promoting safety awareness, collecting safety statistics and measuring occupational safety performance, implementing safety activities such as inspection, chemical and noise exposure control, as well as performing safety audits.

Table 4.1: Profile of Responses

Oil and Gas Company	Platform Operation/ Operation Area in Malaysia	Number of Responses	Approximate Total Number of Health and Safety Personnel*	Approximate Percent Sampling (%)
Dayang Enterprise	Offshore Sarawak	10	15	66.7
JX Nippon	Offshore Sarawak	19	30	63.3
MMC	Offshore Sabah, offshore Sarawak, offshore Terengganu, offshore of Thailand and Malaysia (joint venture)	11	20	55.0
Murphy Oil	Offshore Sabah, offshore Sarawak	18	50	36.0
Petronas Carigali	Offshore Sabah, offshore Sarawak, offshore Terengganu	31	150	20.7
Punj Lloyd	Offshore Sabah	13	20	65.0
ROC Oil	Offshore Sarawak	12	25	48.0
Schlumberger (Malaysia)	Offshore Sabah, offshore Sarawak, offshore Terengganu	18	30	60.0
Shell Malaysia	Offshore Sabah, offshore Sarawak	28	100	28.0
UMW Oil and Gas	Offshore Sabah, offshore Sarawak, offshore Terengganu	12	20	60.0
Total		172	460	

* This is the estimated total population of health and safety personnel in the company. In stratified sampling, the targeted respondents comprised only the health and safety personnel with offshore experience. This could also represent the targeted sample size.

Table 4.2: Work Position of Respondents

Area	Position	Percentage
General Health and Safety	Managerial	5.8
	Executive	49.7
	Assistant	2.1
Process Safety	Managerial	3.3
	Executive	15.8
	Assistant	1.7
Health, Safety and Environment	Managerial	4.2
	Executive	14.5
	Assistant	2.9
	Total	100

Table 4.3: Year of Offshore Work Experience of Respondents

Year of Offshore Work Experience	Percentage
Less than 1 year	4.6
1 year to less than 3 years	21.4
3 years to less than 5 years	20.1
5 years to less than 8 years	33.7
8 years to less than 10 years	10.4
10 years and above	9.8
Total	100

Respondents in the area of process safety comprise technical engineers, process engineers and process safety engineers. These respondents dealt primarily with safety hazard and operability analyses, consequence analyses and risk assessments. They reviewed process-related hazards and identified new process hazards linked to scope and design changes. They also provided recommendations to control process-related hazards. Respondents in the area of health, safety and environment are primarily occupational health and safety experts with role in environmental management such as air emissions and wastewater management. Respondents in managerial positions consist of supervisors, managers and directors while those in executive positions include engineers and officers. Assistants are respondents with roles as technical, health and safety, environmental or engineering assistants. All the respondents have accumulated offshore experience through various work arrangements such as periodic offshore visits, and offshore work shifts. Most respondents have more than 3 years of offshore work experience (see **Table 4.3**).

Cronbach's α uses inter-item correlations to determine whether constituent items are measuring the same domain. If the items show good internal consistency, Cronbach's α should exceed 0.70 for new questionnaire or 0.80 for more established questionnaire (Rattray & Jones, 2007).

The values of Cronbach's α for importance ratings of safety factor and perceived risk due to failure to observe the safety factors were calculated and shown in **Table 4.4**.

Table 4.4: Cronbach's Alpha of Safety Factors

Safety Factor	Perceived Importance	Perceived Risk
Inspection and maintenance	0.857	0.969
Emergency management	0.889	0.963
Management and work engagement (MWE) on safety	0.816	0.904
Number of incidents and near misses	0.916	0.978
Personal safety	0.732	0.935
Contractor safety	0.905	0.953
Plant change/ management of changes	0.911	0.762
Operation and operating procedures	0.876	0.952
Competence	0.706	0.927
Hazard identification and risk assessment	0.86	0.937
Plant design	0.81	0.937
Instrumentation & alarms	0.767	0.934
Documentation	0.819	0.921
Start-ups & shut down	0.834	0.777

Table 4.4 indicates good internal consistency of the survey items under each safety factor, showing that feedbacks from industrial practitioners on the survey items were beneficial.

4.3 Descriptive Statistics of Perceived Importance of Safety Factors and Perceived Risk

Descriptive statistics comprising mean ratings of perceived importance of safety indicators and perceived risk due to failure to observe or implement the corresponding safety indicators, as well as the corresponding variances and standard deviations are presented in **Table 4.5**.

Based on **Table 4.5**, perceived importance ratings of the safety indicators range from 3.35 to 4.40. Two safety indicators with the lowest perceived importance are 'number of out of service equipment' and 'number of days with drilling/ completion activity'. Two safety indicators with the highest perceived importance are 'number of safety critical plant/ equipment that performs within specification when inspected' and 'number of barrier weakness including unsafe conditions identified from MWE'. Standard deviations of the perceived importance ratings range from 0.644 to 1.448.

For perceived risk, the ratings range from 1.88 to 2.91. Two indicators with the lowest perceived risk arising from failure in their implementation and observation are 'number of hazard and operability (HAZOP) actions associated with plant change completed' and 'number of trips, i.e. withdrawals of drill pipe'. Two indicators with the highest perceived risk ratings are 'number of personnel trained on start-ups and shutdowns' and 'the number of safe start-up following changes'. Standard deviations of the perceived risk ratings range from 0.984 to 1.814.

Standard deviation explains the variability of data. A larger standard deviation indicates the data spread over a larger range from the mean. There is a lack of consensus on the acceptable standard deviation for a 5-point Likert survey. Data with very low standard deviation may indicate that the scale or survey item does not effectively discriminate (Kvanli et al., 2005). Generally for normally distributed data, a confidence interval of ±2SD accounts for 95.5% of the survey population, i.e. 95.5% of the responses fall within ±2SD from the mean (Kvanli et al., 2005). The standard deviations in this study are comparable to those of other studies related to safety indicators development (Ng et al., 2005; Skogdalen et al., 2011; Bergh et al., 2014). Normal distributions of the safety factors' mean importance and mean perceived risk ratings are demonstrated via the normal Q-Q plots in **Appendix E**.

Table 4.5: Descriptive Statistics of Safety Indicators

	Safety Indicators	Perceived Importance			Perceived Risk		
		Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
	Safety Factor 1: Inspection & Maintenance						
1	Number of safety critical plant/ equipment that performs within specification when inspected	4.40	0.769	0.877	2.28	1.968	1.403
2	Number of out of service equipment	3.35	2.042	1.429	2.23	1.516	1.231
3	Number of maintenance actions identified that are completed to the specified timescale	3.88	0.677	0.823	2.40	1.340	1.158
4	Number of hours of critical maintenance backlog	3.74	1.623	1.274	2.44	1.300	1.140
5	Number of failure in electrical equipment & units	3.51	1.303	1.142	2.28	1.587	1.260
6	Number of all leaks	4.02	0.642	0.801	2.40	1.673	1.294
	Safety Factor 2: Emergency Management						
7	Number of elements of emergency procedure that fail to function to performance standard	4.26	0.481	0.693	2.35	1.804	1.343
8	Percent staff who take the correct action during emergency events	4.16	0.901	0.949	2.56	1.824	1.351
9	Number of emergency exercises on schedule	4.14	0.599	0.774	2.44	1.157	1.076
	Safety Factor 3: Management and Work Engagement (MWE) on Safety						
10	Percent inspection of work locations completed by manager/ supervisor	4.23	0.516	0.718	2.58	1.154	1.074

	Safety Indicators	Perceived Importance			Perceived Risk		
		Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
11	Percent management & work engagement suggestions implemented	3.95	1.522	1.234	2.33	1.415	1.190
12	Percent safety meetings not fully attended by staff intended	3.91	1.229	1.109	2.49	1.208	1.100
13	Number of barrier weakness including unsafe conditions identified from management & work engagement (MWE)	4.33	0.415	0.644	2.42	1.868	1.367
	Safety Factor 4: Number of Incidents and Near Misses						
14	Number of incidents and near misses attributable to inferior maintenance	3.95	1.236	1.112	2.37	1.811	1.346
15	Number of workplace incidents and near misses due to lack of technical understanding	4.09	0.420	0.648	2.23	2.278	1.509
16	Number of workplace incidents and near misses due to inadequate training	4.07	1.114	1.055	2.44	2.062	1.436
17	Number of workplace incidents and near misses due to lack of skill in team	4.07	1.019	1.009	2.30	1.835	1.355
18	Number of workplace incidents and near misses due to lack of experience	4.07	1.066	1.033	2.26	1.338	1.157
19	Number of incidents resulting from failure to manage change appropriately (e.g. procedural change without following policy)	3.81	1.107	1.052	2.47	1.731	1.316

	Safety Indicators	Perceived Importance			Perceived Risk		
		Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
20	Number of incidents involving loss of containment of hazardous material due to inadequate plant design	4.07	0.495	0.704	2.30	1.835	1.355
21	Number of incidents of plant breakdown due to inadequate plant design	3.88	1.058	1.028	2.14	1.647	1.283
22	Number of incidents during start-ups and shutdown	4.16	1.235	1.111	2.44	1.919	1.385
23	Number of incidents where plant/ equipment could be damaged due to failure to control high-risk maintenance	4.02	1.166	1.080	2.42	1.725	1.314
24	Number of incidents and near misses caused by contractors or visitors	3.77	1.754	1.324	2.47	1.207	1.099
25	Number of incidents where operational shortcuts were identified	3.79	1.455	1.206	2.56	1.776	1.333
	Safety Factors 5: Personal Safety						
26	Number of exceedance of noise level beyond actionable level of 85dB(A)	4.09	1.182	1.087	2.26	1.719	1.311
27	Number of occupational disease cases reported	3.84	1.473	1.214	2.51	2.065	1.437
28	Number of occupational poisoning cases reported	3.63	1.382	1.176	2.65	1.709	1.307
29	Number of food poisoning cases reported	3.65	1.471	1.212	2.53	1.540	1.241
30	Number of employees affected by chronic/ acute fatigue at work	3.84	1.092	1.045	2.30	1.692	1.301

	Safety Indicators	Perceived Importance			Perceived Risk		
		Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
31	Overtime working hours (over a fixed duration)	3.98	0.928	0.963	2.35	1.090	1.044
32	Number of extended shifts per person (over a fixed duration)	3.79	1.693	1.301	2.44	1.252	1.119
33	Number of exceedances of Permissible Exposure Limits for chemicals hazardous to health	3.84	0.759	0.871	2.35	1.423	1.193
34	Number of medical surveillance showing exceeded threshold values	4.23	0.754	0.868	2.44	1.729	1.315
	Safety Factor 6: Contractor Safety						
35	Percent contractors' act in accordance with company's policy	3.74	1.100	1.049	2.40	1.816	1.348
36	Number of open/ unresolved contractors' safety suggestions	3.70	1.073	1.036	2.30	1.787	1.337
	Safety Factor 7: Plant Change/ Management of Changes						
37	Number of times equipment or plant is below desired standard due to deficiencies in plant change	3.67	1.558	1.248	2.05	1.617	1.272
38	Number of hazard and operability (HAZOP) actions associated with plant change completed	4.12	1.058	1.028	1.88	1.772	1.331
39	Number of plant change actions undertaken where authorization was given before implementation	3.81	1.488	1.220	2.19	1.965	1.402
40	Number of management of change (MOCs) in compliance with procedure	3.84	1.616	1.271	2.33	1.606	1.267

	Safety Indicators	Perceived Importance			Perceived Risk		
		Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
41	Number of emergency changes/ requests for emergency changes	4.23	0.945	0.972	2.42	1.535	1.239
42	Number of safe start-up following changes	3.74	1.528	1.236	2.88	1.613	1.274
	Safety Factor 8: Operation and Operating Procedures						
43	Percent/ number of operation within design limits	3.84	1.092	1.045	2.42	1.440	1.200
44	Length of time plant is in production with safety critical plant or equipment in failed state	3.91	1.753	1.324	2.23	1.897	1.377
45	Total number of safety instrumentation and alarms activations reported by operation	3.65	1.614	1.270	2.44	2.014	1.419
46	Number of days with drilling/ completion activity	3.37	2.096	1.448	2.33	2.749	1.658
47	Number of days with workover	3.72	0.920	0.959	2.09	2.086	1.444
48	Number of trips, i.e. withdrawals of drill pipe	4.12	0.629	0.793	2.00	1.667	1.291
49	Number of exceedances of allowed burning time in restricted areas	3.88	0.486	0.697	2.47	1.588	1.260
50	Percent/ number of safety critical tasks for which a written operational procedure covers the correct scope	3.84	1.949	1.396	2.77	1.087	1.043
51	Percent/ number of clear and understandable procedures	3.81	1.774	1.332	2.53	0.969	0.984
52	Percent/ number of reviewed and revised procedures within the designated period	4.07	0.590	0.768	2.70	1.549	1.245

	Safety Indicators	Perceived Importance			Perceived Risk		
		Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
53	Number of PHA recommendations related to inadequate operating procedures	3.84	1.140	1.067	2.56	1.729	1.315
	Safety Factor 9: Competence						
54	Number of experienced area operators	4.09	1.277	1.130	2.51	1.684	1.298
55	Percent/ number of time that asset integrity/ process safety critical positions have gone unstaffed	4.19	1.012	1.006	2.63	1.906	1.381
56	Number of individuals who completed a planned PSM (Process Safety Management) training	3.84	1.949	1.396	2.65	1.566	1.251
	Safety Factor 10: Hazard Identification & Risk Assessment						
57	Number of completed hazard identification & risk assessment	3.79	1.646	1.283	2.65	1.518	1.232
58	Number of P&ID (Process & Instrument Diagram) corrections and other actions identified during process hazard analyses	3.84	1.568	1.252	2.49	1.351	1.162
59	Average number of hours per process & instrument diagram (P&ID) for conducting baseline & revalidation of PHA (process hazard analysis)	3.93	0.733	0.856	2.53	1.398	1.182
	Safety Factor 11: Plant Design						
60	Percent/ number of safety critical equipment or components of plant which comply with current design standards or codes	3.86	1.409	1.187	2.37	1.906	1.381

	Safety Indicators	Perceived Importance			Perceived Risk		
		Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
61	Percent/ number of replacement of inferior components or systems with safer ones	4.30	0.549	0.741	2.47	1.540	1.241
62	Number of post-startup modifications required	3.79	1.503	1.226	2.09	1.515	1.231
	Safety Factor 12: Instrumentation & Alarms						
63	Number of failure of safety critical instruments/ alarms, either in use or during testing	4.05	0.760	0.872	2.26	1.433	1.197
64	Number of safety instrumentation and alarms faults during tests	4.30	0.692	0.832	2.58	1.916	1.384
65	Number of safety critical instruments and alarms that activate at desired set point	3.86	1.504	1.226	2.51	1.827	1.352
66	Number of functional tests of safety critical instruments and alarms completed to schedule	4.12	0.962	0.981	2.58	1.630	1.277
	Safety Factor 13: Documentation						
67	Number of facility related safety documents completed as per corporate and legal requirement	4.09	1.134	1.065	2.72	1.444	1.202
68	Number of facility related safety documents retained as per corporate and legal requirement	4.16	0.949	0.974	2.81	1.107	1.814
	Safety Factor 14: Start-ups and shutdown						
69	Number of deferred start-up & unplanned shutdown	4.09	0.991	0.996	2.79	1.408	1.186

	Safety Indicators	Perceived Importance			Perceived Risk		
		Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
70	Number of personnel trained on start-ups and shutdowns	4.21	0.884	0.940	2.91	1.753	1.324

The indicators are grouped under 14 safety factors as indicated in **Table 4.5** and **Table 4.6**. **Table 4.6** shows the descriptive statistics of the safety factors' perceived importance and perceived risk in the event of failing to observe the factors, encompassing means, variances and standard deviations. The perceived importance and risk are also demonstrated in **Figure 4.1**.

Table 4.6: Descriptive Statistics for Perceived Importance of Safety Factors and Perceived Risk due to Failure to Observe Safety Factors

No.	Safety Factors	Perceived Importance			Perceived Risk*		
		Mean	Variance	Standard Deviation	Mean	Variance	Standard Deviation
1	Inspection and maintenance	3.818	0.686	0.828	2.337	1.355	1.164
2	MWE on safety	4.105	0.593	0.770	2.454	1.096	1.046
3	Number of incidents and near misses	3.981	0.577	0.760	2.366	1.442	1.201
4	Contractor safety	3.721	0.992	0.996	2.349	1.721	1.312
5	Management of plant change	3.903	0.946	0.973	2.291	1.509	1.229
6	Plant operations and operating procedures	3.822	0.546	0.739	2.412	0.874	0.935
7	Competence	4.039	0.890	0.943	2.597	1.500	1.225
8	Plant design	3.985	0.836	0.914	2.310	1.468	1.211
9	Instrumentation and alarms	4.081	0.577	0.759	2.483	1.421	1.192
10	Documentation	4.128	0.882	0.939	2.767	1.183	1.088
11	Start-ups and shutdown	4.151	0.804	0.897	2.849	1.292	1.137
12	Personal safety	3.876	0.632	0.795	2.426	1.219	1.104
13	Hazard identification and risk assessment	3.851	1.031	1.015	2.558	1.263	1.124
14	Emergency management	4.186	0.430	0.656	2.450	1.412	1.188

* Due to failure in observing the indicators.

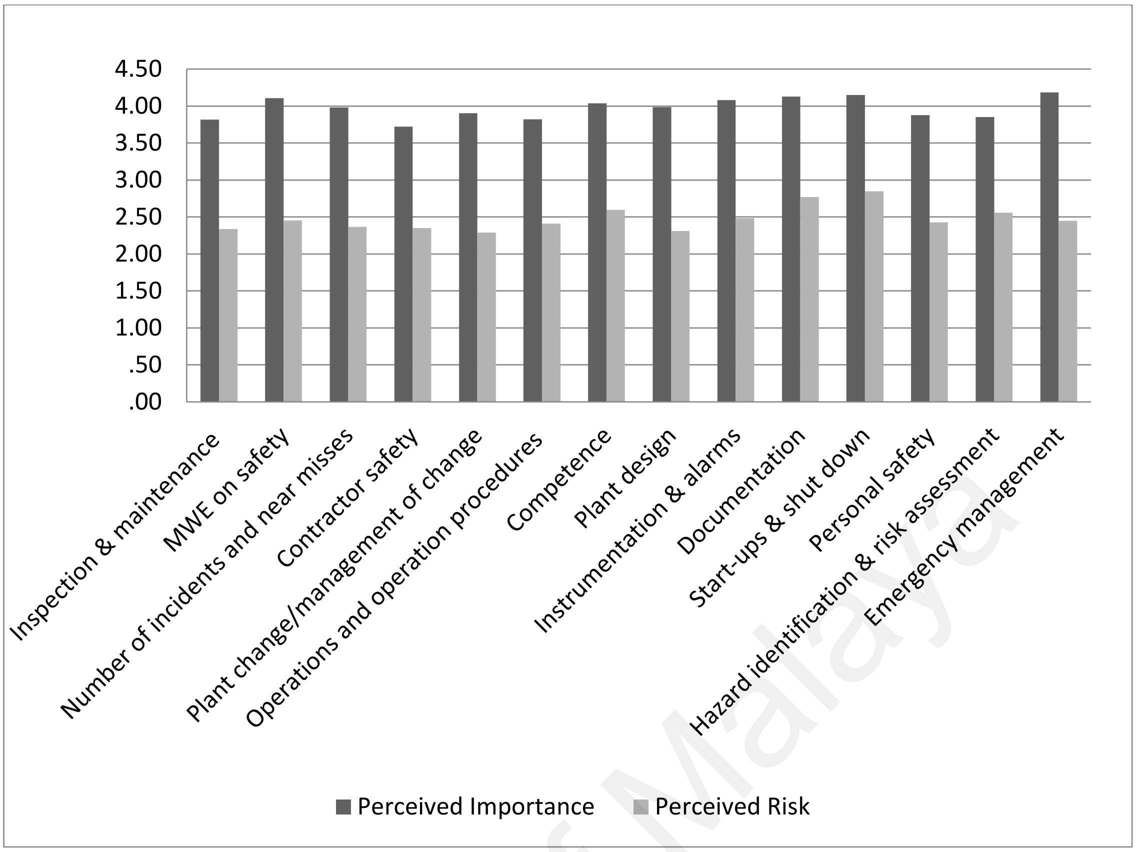


Figure 4.1: Perceived Importance and Risk of Safety Factors

Referring to **Table 4.6** and **Figure 4.1**, perceived importance ratings of the safety factors show all the factors have above moderate importance. Five most important factors in descending order are emergency management (mean = 4.19), start-ups and shutdown (mean = 4.15), documentation (mean = 4.13), MWE on safety (mean = 4.10) and instrumentation & alarms (mean = 4.03).

Perceived risk due to failure to observe the safety factors demonstrates low to medium ratings, with start-ups and shut-down having the highest perceived risk (mean = 2.85) in the event the underpinning indicators are not adequately observed. This is followed by documentation (mean = 2.77), competence (mean = 2.60), hazard identification and risk assessment (mean = 2.56), as well as instrumentation & alarms (mean = 2.48).

Of the 5 safety factors having the highest perceived importance ratings, three are also in the top 5 ranking of perceived risk i.e. start-up and shutdown, documentation and instrumentation & alarm. Start-up and shutdown has the second highest perceived importance ranking and the highest perceived risk ranking (refer **Table 4.7**). Documentation is ranked the third in terms of perceived importance and second in terms of perceived risk while instrumentation & alarms is ranked the fifth for both perceived importance and perceived risk. **Table 4.7** shows comparative ranking of perceived importance and perceived risk of the safety factors.

Four safety factors have differences in the ranking of perceived importance and perceived risk greater than 3, i.e. emergency management, number of incidents and near misses, management of change as well as hazard identification and risk assessment (see **Table 4.7**). The rank difference simply implies a difference in perception of the two survey facets among the same respondents.

Table 4.7: Comparative Ranking of Perceived Importance and Perceived Risk of Safety Factors

Safety Factor	**Rank**		**Rank Difference** [a]
	Perceived Importance	**Perceived Risk**	
Emergency management	1	6*	5
Start-ups and shutdown	2	1	1
Documentation	3	2	1
MWE on safety	4	6*	2
Instrumentation and alarms	5	5	0
Competence	6	3	3
Plant design	7*	9*	2
Number of incidents and near misses	7*	11*	4
Management of plant change	9	14	5
Personal safety	10	8	2
Hazard identification and risk assessment	11	4	7

Safety Factor	Rank		Rank Difference [a]
	Perceived Importance	Perceived Risk	
Plant operations and operating procedures	12*	9*	3
Inspection and maintenance	12*	13	1
Contractor safety	14	11*	1

* Where two safety factors have the same rank, the following rank is skipped.

[a] Rank difference means the difference in the perceived importance and perceived risk ranking of a safety factor.

Generally, perceived risk ratings of the safety factors are lower than the perceived importance ratings. To provide an overview of the relationship between perceived importance and perceived risk, a graph of mean perceived risk due to failure to observe the safety factors against mean perceived importance of the safety factors is plotted as shown in **Figure 4.2**. Linear regression based on least square approach shows a weak positive correlation between both ratings, indicating that a change in mean perceived importance rating produces a smaller change in mean perceived risk rating. This implies that the perceived risk rating is very weakly affected by the perceived importance rating which is confirmed in the plot of mean perceived risk ratings of the individual indicators against their corresponding mean perceived importance ratings (**Figure 4.3**).

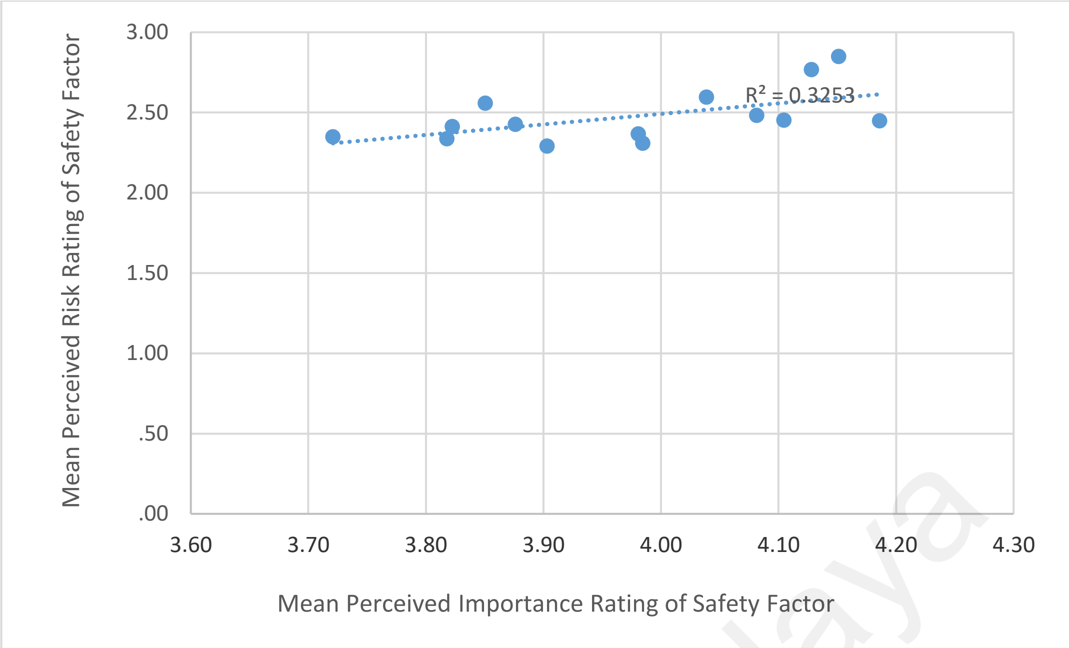


Figure 4.2: Mean Perceived Risk against Mean Perceived Importance Ratings of Safety Factors

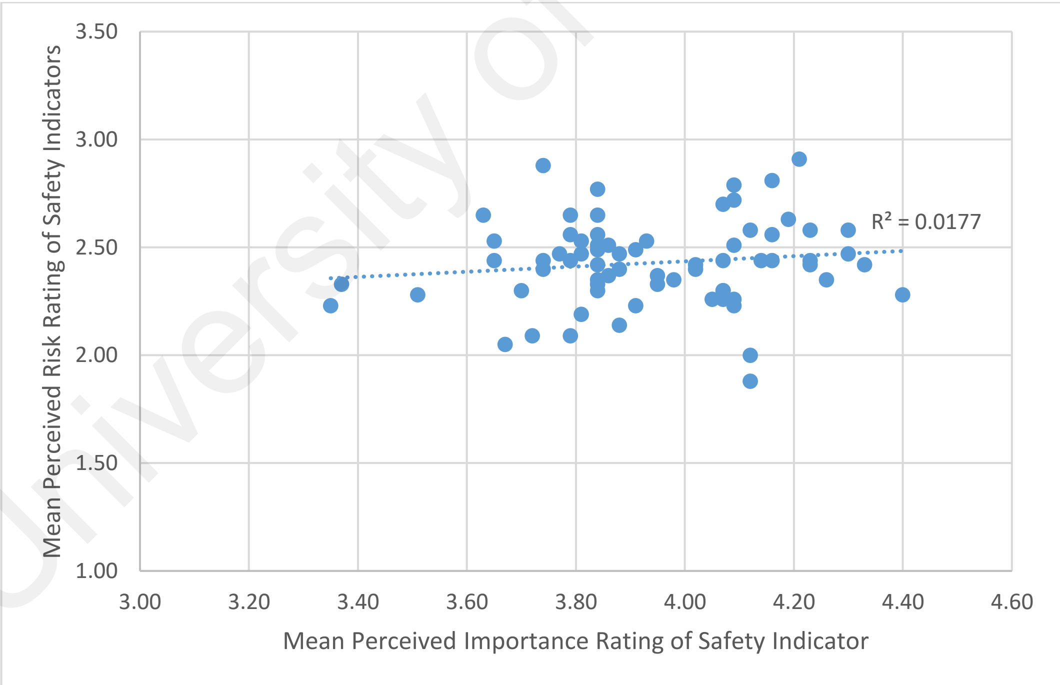


Figure 4.3: Mean Perceived Risk against Mean Perceived Importance Ratings of Safety Indicators

4.4 Correlations between Safety Factors

4.4.1 Factor Analysis of Perceived Importance Ratings of Safety Factors

Factor analysis shows the correlations between the safety factors. Certain safety factors are more connected than the others by eliciting a particular pattern of characteristics. This pattern of characteristics is useful for identification of overarching factors affecting safety of offshore oil and gas installations. Kaiser-Meyer-Olkin Measure of Sampling Adequacy shows 0.728 which is higher than the minimum of 0.6 suggested (Mulaik, 2010). Factor extraction, i.e. grouping of variables or safety factors were conducted by means of principal component analysis where uncorrelated linear variable combinations called components are generated with the first component accounting for the largest variance and subsequent components explaining decreasing variances successively (refer **Table 4.8**) (IBM, 2014).

The scree plot generated from factor analysis is shown in **Figure 4.4**. Scree plot shows eigenvalue plotted against number of safety component for identification of the number of component accounting for most of the data variability. Eigenvalue presents variances of the safety components in a correlation matrix with components having the highest eigenvalue accounting for the most variance. The number of components chosen has eigenvalue equal to and higher than 1. **Figure 4.4** and **Table 4.8** shows three components explain 80% of the variance, hence the eigenvalue at and above 1. Three overarching components were selected for grouping of the safety factors (refer **Table 4.7**).

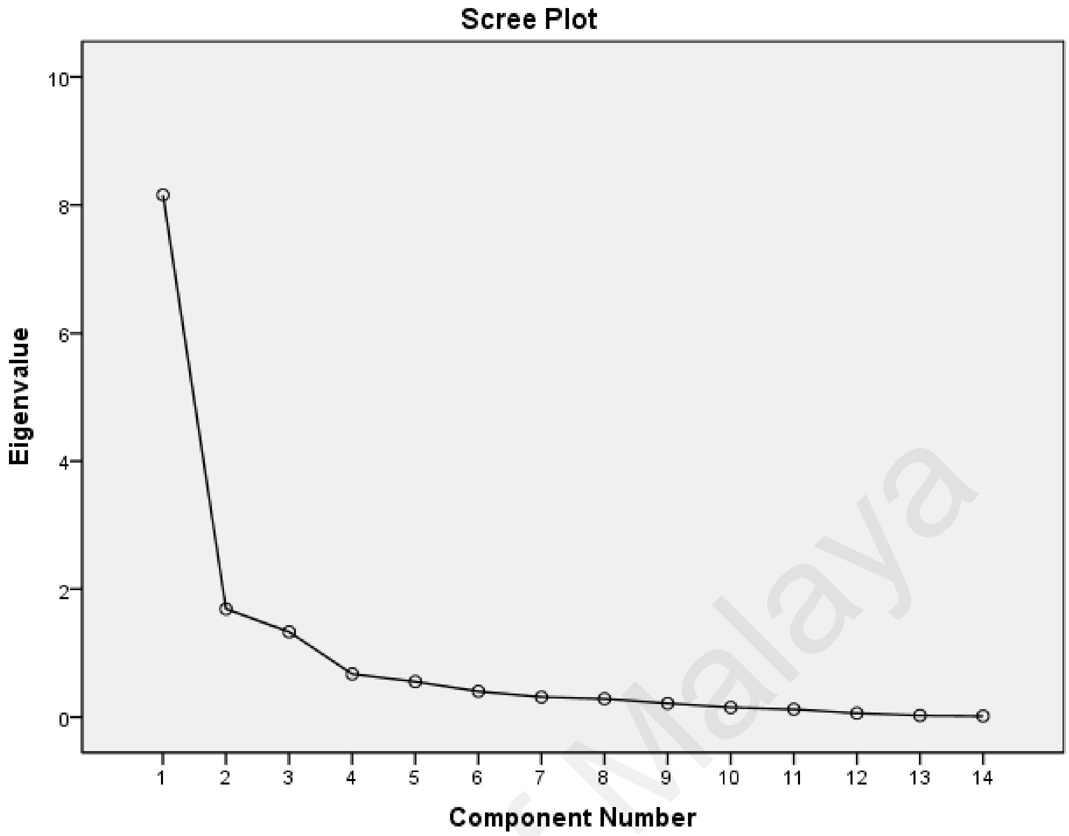


Figure 4.4: Scree Plot Based on Mean Perceived Importance Ratings

Table 4.8: Total Variance Explained for Perceived Importance of Safety Factors

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	8.160	58.287	58.287
2	1.690	12.070	70.357
3	1.331	9.507	79.863
4	0.673	4.810	84.673
5	0.554	3.956	88.629
6	0.402	2.873	91.502
7	0.313	2.238	93.740
8	0.286	2.041	95.780
9	0.215	1.538	97.318
10	0.152	1.083	98.402
11	0.122	0.873	99.274
12	0.060	0.428	99.703
13	0.025	0.179	99.882
14	0.017	0.118	100.000

The rotated component matrix of factor analysis is shown in **Table 4.9**. The 14 safety factors identified are grouped under three components. Safety factors grouped under the same component are more correlated than those in other components. Safety factors with factor loadings of 0.40 or greater are considered as significant (Morrow et al., 2014). The factor loading indicates how related the safety factors, i.e. the variables are to the overarching components. For instance, inspection and maintenance is significantly correlated to Component 3 with a factor loading of 0.794. In the instance where a safety factor is significantly correlated with two components, the higher factor loading determines the component it is grouped under.

Table 4.9: Rotated Component Matrix

Safety Factor	**Component/ Group**		
	1	***2***	***3***
Inspection and maintenance			0.794
MWE on safety	0.654		0.625
Number of incidents and near misses	0.907		
Contractor safety	0.896		
Management of plant change	0.811		
Plant operations and operating procedures	0.782		
Competence		0.792	
Plant design	0.751		
Instrumentation & alarms		0.851	
Documentation		0.747	
Start-ups and shutdown		0.738	
Personal safety	0.719		
Hazard identification and risk assessment	0.865		
Emergency management			0.866

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.[a]

a. Rotation converged in 6 iterations.

Factor analysis of the perceived importance ratings identifies three groups of correlated safety factors (see **Table 4.9**). The first group comprises 8 safety factors, i.e. MWE on safety, number of incidents and near misses, contractor safety, plant operations and operating procedures, plant design, personal safety as well as hazard identification and risk assessment. The second group consists of competence, instrumentation and alarms, documentation as well as start-ups and shut down. The third group comprises inspection and maintenance, MWE on safety and emergency management (**Table 4.9**).

4.4.2 Hierarchical Clustering of Perceived Importance Ratings of Safety Factors

Figure 4.5 shows the dendrogram using average linkage (between groups) based on the perceived importance ratings of the safety factors. Hierarchical clustering depicts two main clusters of factors. The result of hierarchical clustering is comparable to that of factor analysis. The lower cluster in the dendrogram consists of the same safety factors as group 2 in factor analysis (see **Table 4.9** and **Figure 4.5**). The upper cluster branches into two sub-clusters, one corresponds to group 1 in factor analysis and another corresponds to group 3. The results of both analyses agree well with hierarchical clustering showing more detailed relationship between the factors.

The horizontal axis represents increasing dissimilarity between clusters. From the dendrogram (**Figure 4.5**), it can be seen that perceived importance of number of incidents & near misses are very closely related to perceived importance of personal safety. In addition, perceived importance of plant operation & operating procedures are closely related to perceived importance of hazard identification and risk assessment.

Taking the lower cluster for instance, the dendrogram (**Figure 4.5**) shows perceived importance of instrumentation & alarm is more closely related to perceived importance of documentation than perceived importance of competence, whereas perceived importance of start-up and shutdown is most dissimilar to the other factors.

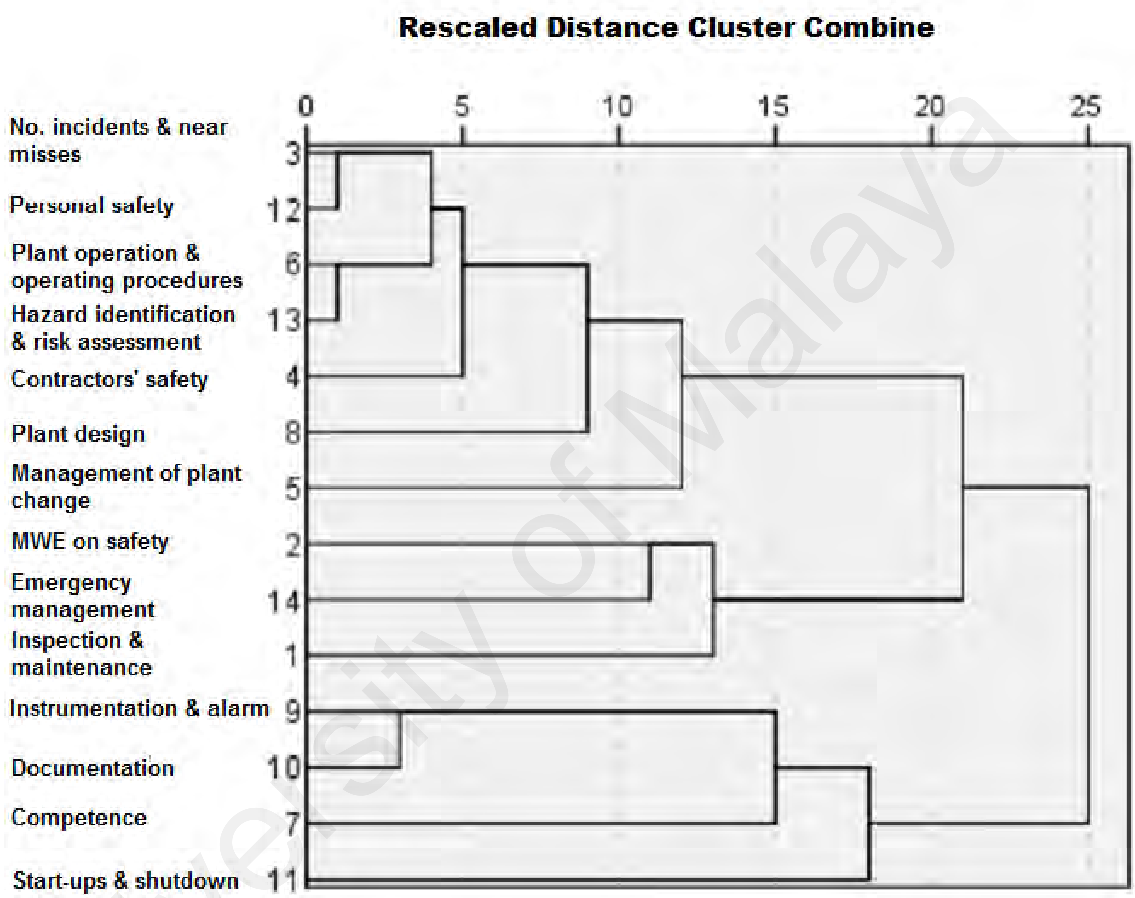


Figure 4.5: Dendrogram for Perceived Importance of Safety Factors using Average Linkage (Between Groups)

4.4.3 Factor Analysis of Perceived Risk Ratings of Safety Factors

Factor analysis is also conducted to investigate how the safety factors are related based on the perceived risk ratings. Kaiser-Meyer-Olkin Measure of Sampling Adequacy shows 0.765 which is higher than the minimum of 0.6 suggested (Mulaik, 2010).

Scree plot in **Figure 4.6** shows two components explain most of the variability, hence having eigenvalue higher than 1. Details of the explained variance are shown in **Table 4.10**. The first two components explain 86.6% of the variance.

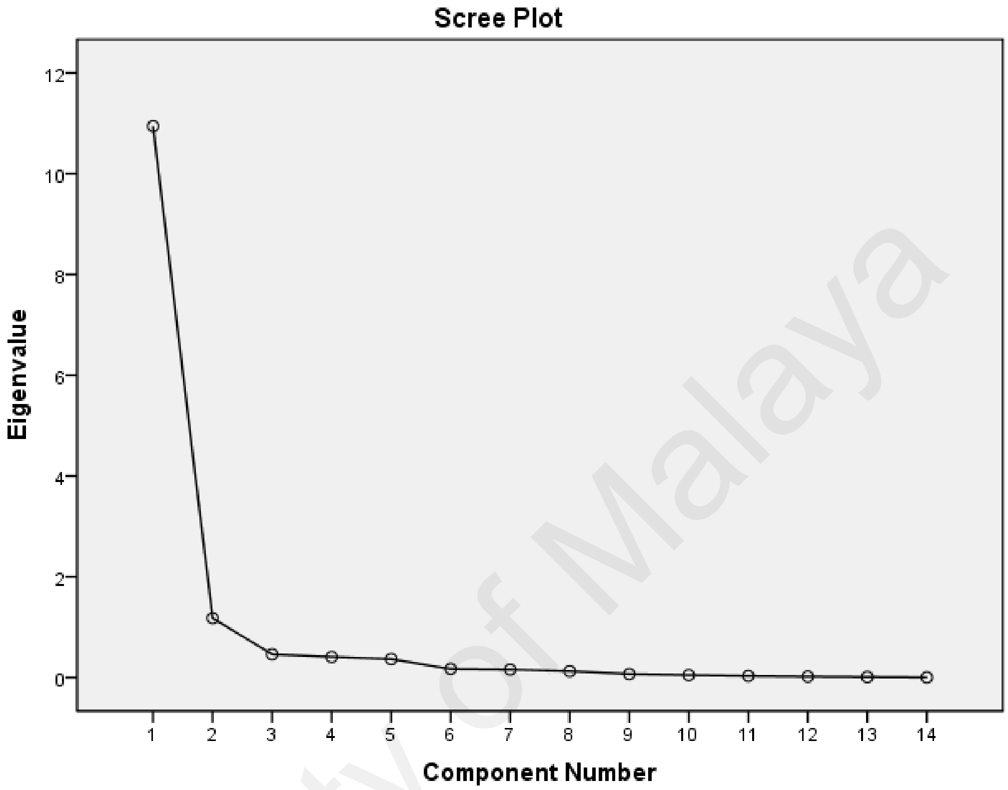


Figure 4.6: Scree Plot Based on Mean Perceived Risk Ratings

Table 4.10: Total Variance Explained for Perceived Risk of Safety Factors

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	10.940	78.170	78.170
2	1.180	8.425	86.595
3	0.463	3.309	89.904
4	0.408	2.912	92.817
5	0.368	2.625	95.442
6	0.170	1.213	96.655
7	0.159	1.135	97.790
8	0.126	0.903	98.694
9	0.069	0.494	99.188
10	0.048	0.342	99.530
11	0.032	0.228	99.758
12	0.020	0.140	99.899
13	0.011	0.079	99.977
14	0.003	0.023	100.000

The rotated component matrix in **Table 4.11** shows that component 1 consists of contractor safety, management of plant change, plant operations and operating procedures, competence, plant design, instrumentation and alarms, documentation, start-ups and shutdown as well as hazard identification and risk assessment. Component 2 comprises inspection and maintenance, MWE on safety, number of incidents and near misses, personal safety and emergency management.

Table 4.11: Rotated Component Matrix

Safety Factor	**Component/ Group**	
	1	***2***
Inspection and maintenance		0.939
MWE on safety		0.881
Number of incidents and near misses		0.808
Contractor safety	0.780	
Management of plant change	0.721	
Plant operations and operating procedures	0.721	
Competence	0.877	
Plant design	0.760	
Instrumentation & alarms	0.723	
Documentation	0.767	
Start-ups and shut down	0.838	
Personal safety		0.689
Hazard identification and risk assessment	0.867	
Emergency management		0.913

Extraction Method: Principal Component Analysis.

Rotation Method: Varimax with Kaiser Normalization.[a]

a. Rotation converged in 6 iterations.

Table 4.12 shows a comparison between the safety factors combinations based on factor analysis performed on perceived importance ratings and perceived risk ratings. Similarity in component 1 of both analyses as well as between component 3 of factor analysis of mean perceived importance ratings and component 2 of factor analysis of mean perceived risk ratings can be observed.

Table 4.12: Comparison of Safety Factors Combinations from Factor Analysis of Mean Perceived Importance Ratings and Mean Perceived Risk Ratings

	Component/ Group		
	1	2	3
Combination of safety factors from factor analysis of mean perceived importance ratings	• MWE on safety • Number of incidents and near misses • **Contractor safety** • **Management of plant change** • **Plant operations and operating procedures** • **Plant design** • Personal safety • **Hazard identification and risk assessment**	• Competence • Instrumentation & alarms • Documentation • Start-ups and shutdown	• **Inspection and maintenance** • **MWE on safety** • **Emergency management**
Combination of safety factors from factor analysis of mean perceived risk ratings	• **Contractor safety** • **Management of plant change** • **Plant operations and operating procedures** • Competence • **Plant design** • Instrumentation & alarms • Documentation • Start-ups and shut down • **Hazard identification and risk assessment**	• **Inspection and maintenance** • **MWE on safety** • Number of incidents and near misses • Personal safety • **Emergency management**	Nil

Note: Safety factors showing similar grouping in the factor analysis based on perceived importance ratings and perceived risk ratings respectively are bolded.

4.4.4 Hierarchical Clustering of Perceived Risk Ratings of Safety Factors

Figure 4.7 shows dendrogram using average linkage (between groups) based on the perceived importance ratings of the safety factors. Hierarchical clustering depicts two main clusters of factors. The upper cluster can be subdivided into two sub-clusters with the top sub-cluster comprises MWE on safety, emergency management, inspection and maintenance, number of incidents and near misses and personal safety, while the bottom sub-cluster comprises plant design, instrumentation and alarm and contractor safety. The lower cluster consists of competence, hazard identification and risk assessment, documentation as well as start-ups and shutdown.

A comparison of the dendrogram with the factor analysis results shows that safety factors in component 2 (**Table 4.11**) are similar to the top sub-cluster in the upper cluster of the dendrogram (**Figure 4.7**) while safety factors in component 1 (**Table 4.11**) are similar to those in the remaining parts of the dendrogram. It can be observed that, similar to perceived importance, perceived risk of MWE on safety is closely related to perceived risk of emergency management while perceived risk of number of incidents and near misses is closely related to perceived risk of personal safety.

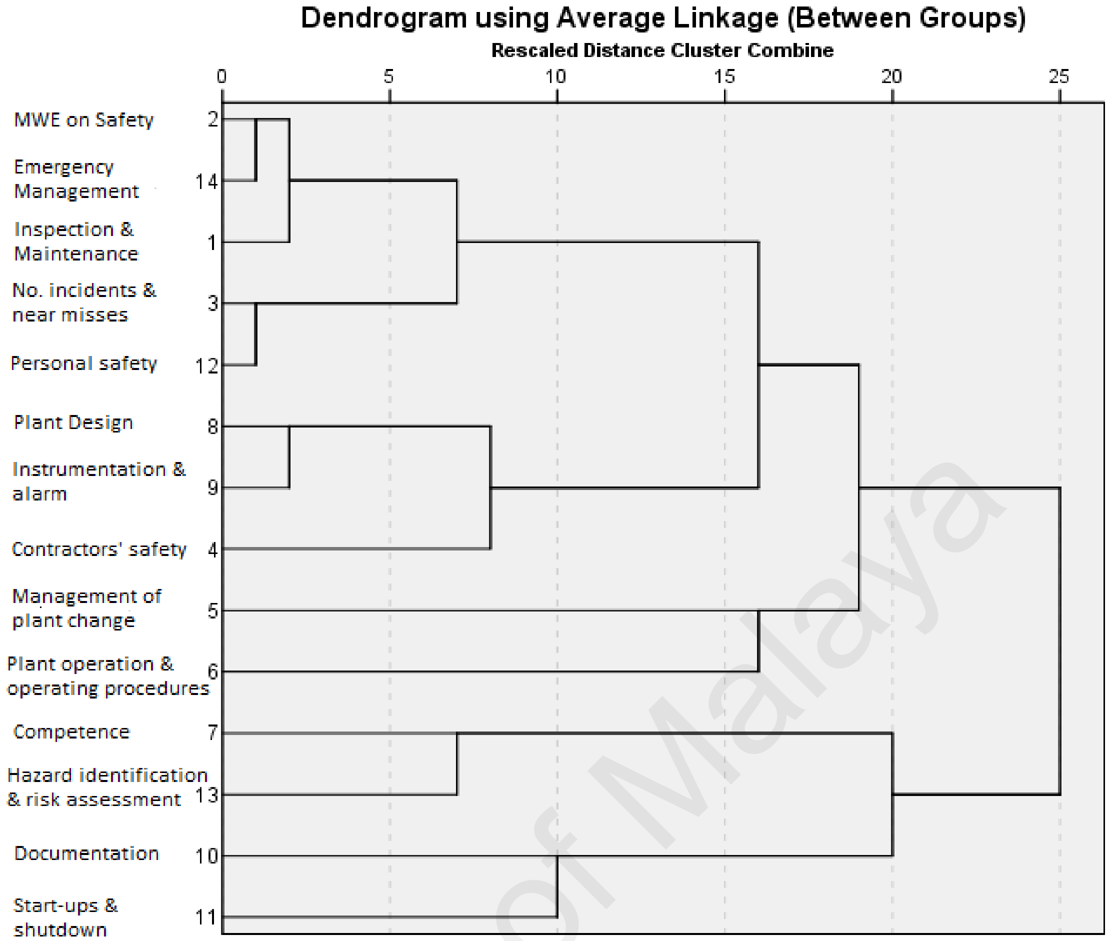


Figure 4.7: Dendrogram for Perceived Risk of Safety Factors using Average Linkage (Between Groups)

4.4.5 Correlations between Perceived Importance and Perceived Risk Ratings

A plot of mean perceived importance ratings and mean perceived risk ratings of the safety factors in **Figure 4.2** shows a weak positive correlation which is not entirely linear. Pearson correlation is used to examine the correlations in a more detailed manner (Eisinga et al., 2013).

Generally, the correlations between mean perceived importance ratings and mean perceived risk ratings are weak with correlation coefficients less than 0.5, confirming the low R-squared value shown in **Figure 4.2**. At significance level of 0.01, the followings can be considered significant (also see **Table 4.13**):

- Perceived importance of MWE on safety is correlated with perceived risk of failing to observe instrumentation and alarms, documentation as well as start-ups and shutdown
- Perceived importance of number of incidents and near misses is correlated with perceived risk of failing to observe instrumentation and alarms, start-ups and shutdown, as well as hazard identification and risk assessment.
- Perceived importance of management of plant change is correlated with perceived risk of failing to observe contractor safety, competence, plant design, instrumentation and alarms, as well as hazard identification and risk assessment.
- Perceived importance of plant design is correlated with contractor safety, competence, instrumentation and alarms, as well as hazard identification and risk assessment.
- Perceived importance of personal safety is correlated with perceived risk of failing to observe instrumentation and alarms as well as hazard identification and risk assessment.

The correlations listed above are positive, i.e. respondents who perceive a safety factor as important also tend to perceive higher risk of failing to observe the correlating safety factors.

Table 4.13: Pearson Correlation between Perceived Importance and Perceived Risk Ratings

Perceived Importance	Perceived Risk													
	Inspection and Maintenance	MWE on safety	Number of incidents and near misses	Contractor Safety	Management of plant change	Plant operation and operating procedures	Competence	Plant design	Instrumentation and alarms	Documentation	Start-ups and shutdown	Personal Safety	HIRA	Emergency management
Inspection and maintenance	-0.237	-0.158	0.011	0.005	0.104	0.259*	0.204	-0.035	0.085	0.064	0.248	0.033	0.341*	-0.106
MWE on safety	-0.006	0.093	0.166	0.219	0.209	0.338**	0.406**	0.279*	**0.375****	**0.371****	**0.450****	0.247	0.486**	0.073
Number of incidents and near misses	0.109	0.125	0.242	0.321*	0.233	0.239	0.339*	0.335*	**0.413****	0.267*	**0.426****	0.210	**0.464****	0.152
Contractor safety	-0.008	-0.010	0.113	0.131	0.112	0.068	0.202	0.192	0.272*	0.082	0.125	0.083	0.277*	0.055
Management of plant change	0.133	0.156	0.315*	**0.358****	0.276*	0.121	**0.411****	**0.422****	**0.465****	0.194	0.107	0.240	**0.422****	0.250
Plant operations and operating procedures	-0.129	-0.164	-0.012	0.066	0.053	0.067	0.190	0.063	0.142	0.008	0.079	-0.037	0.278*	-0.079
Competence	0.070	-0.060	-0.012	-0.075	-0.035	-0.090	-0.217	-0.177	-0.047	-0.204	-0.194	-0.157	0.012	0.055
Plant design	0.097	0.107	0.319*	**0.408****	0.200	0.296*	**0.448****	0.282*	**0.377****	0.168	0.288*	0.307*	**0.472****	0.184
Instrumentation and alarms	-0.037	0.018	0.011	-0.005	-0.074	-0.002	0.036	-0.099	0.044	-0.016	0.046	-0.101	0.166	0.029
Documentation	-0.002	-0.060	-0.045	0.098	0.089	0.021	0.084	-0.004	0.087	0.030	0.136	-0.087	0.224	-0.010
Start-ups and shutdown	-0.120	-0.097	-0.088	-0.056	-0.156	-0.124	-0.059	-0.146	-0.028	-0.238	-0.146	-0.160	0.123	-0.062
Personal safety	0.146	0.159	0.326*	0.345*	0.231	0.249	0.242	0.294*	**0.404****	0.143	0.295*	0.260*	**0.459****	0.220
Hazard identification and risk assessment	-0.119	-0.182	-0.023	0.108	0.090	0.048	0.121	0.109	0.142	0.029	0.142	-0.041	-0.220	-0.121

Perceived Importance	Perceived Risk													
	Inspection and Maintenance	MWE on safety	Number of incidents and near misses	Contractor Safety	Management of plant change	Plant operation and operating procedures	Competence	Plant design	Instrumentation and alarms	Documentation	Start-ups and shutdown	Personal Safety	HIRA	Emergency management
Emergency management	-0.065	-0.080	0.049	0.250	0.179	0.115	0.198	0.109	0.192	0.184	0.337*	0.105	0.337*	0.012

**. Correlation is significant at the 0.01 level (1-tailed)

*. Correlation is significant at the 0.05 level (1-tailed)

4.4.6 Pearson Correlation between Perceived Importance Ratings of Safety Factors

To further confirm the correlations between perceived importance ratings of the safety factors elucidated via factor analysis and hierarchical clustering, Pearson correlation of perceived importance ratings of the safety factors were conducted. The results are shown in **Table 4.14**.

Pearson's r in **Table 4.14** are generally in line with hierarchical clustering in **Figure 4.5**, with number of incidents and near misses showing highest r with personal safety; plant operation & operating procedures showing highest r with hazard identification and risk assessment; and instrumentation and alarms demonstrating highest r with competence. Correlations with $r > 0.5$ are generally shown by safety factors grouped under the same sub-cluster. For instance, Pearson correlation reveals that perceived importance of management of plant change is positively and significantly correlated with perceived importance of number of incidents and near-misses, contractor safety, plant operation and operating procedures, plant design, personal safety as well as hazard identification and risk assessment respectively. This corresponds to the top sub-cluster in **Figure 4.5**.

Table 4.14: Pearson Correlation of Safety Factors Based on Perceived Importance

Perceived Importance	Perceived Importance													
	Inspection and Maintenance	MWE on safety	Number of incidents and near misses	Contractor Safety	Management of plant change	Plant operation and operating procedures	Competence	Plant design	Instrumentation and alarms	Documentation	Start-ups and shutdown	Personal Safety	HIRA	Emergency management
Inspection and maintenance	1	**0.592**	0.450	0.435	0.196	**0.577**	0.441	0.403	0.455	0.441	0.310	**0.589**	0.466	**0.675**
MWE on safety	**0.592**	1	**0.710**	**0.644**	0.443	**0.682**	0.180	**0.569**	0.227	0.298	0.274	**0.645**	**0.691**	**0.514**
Number of incidents and near misses	0.450	**0.710**	1	**0.843**	**0.664**	**0.783**	0.282	**0.728**	0.435	**0.625**	0.229	**0.827**	**0.891**	0.296
Contractor safety	0.435	**0.644**	**0.843**	1	**0.772**	**0.832**	0.367	**0.745**	**0.542**	**0.637**	0.308	**0.818**	**0.835**	0.282
Management of plant change	0.196	0.443	**0.664**	**0.772**	1	**0.712**	0.376	**0.672**	0.410	0.442	0.242	**0.645**	**0.655**	0.203
Plant operations and operating procedures	**0.577**	**0.682**	**0.783**	**0.832**	**0.712**	1	**0.577**	**0.776**	**0.617**	**0.724**	0.419	**0.745**	**0.889**	0.445
Competence	0.441	0.180	0.282	0.367	0.376	**0.577**	1	0.320	**0.655**	**0.603**	**0.537**	**0.516**	0.461	0.411
Plant design	0.403	**0.569**	**0.728**	**0.745**	**0.672**	**0.776**	0.320	1	**0.556**	**0.589**	0.453	**0.796**	**0.680**	0.398
Instrumentation and alarms	0.455	0.227	0.435	**0.542**	0.410	**0.617**	**0.655**	**0.556**	1	**0.820**	**0.580**	**0.559**	0.411	0.236
Documentation	0.441	0.298	**0.625**	**0.637**	0.442	**0.724**	**0.603**	**0.589**	**0.820**	1	**0.535**	**0.605**	**0.621**	0.315
Start-ups and shutdown	0.310	0.274	0.229	0.308	0.242	0.419	**0.537**	0.453	**0.580**	**0.535**	1	**0.547**	0.261	0.417
Personal safety	**0.589**	**0.645**	**0.827**	**0.818**	**0.645**	**0.745**	**0.516**	**0.796**	**0.559**	**0.605**	**0.547**	1	**0.770**	**0.516**
HIRA	0.466	**0.691**	**0.891**	**0.835**	**0.655**	**0.889**	0.461	**0.680**	0.411	**0.621**	0.261	**0.770**	1	0.341
Emergency management	**0.675**	**0.514**	0.296	0.282	0.203	0.445	0.411	0.398	0.236	0.315	0.417	**0.516**	0.341	1

Note: The bolded figures show significant correlation at the 0.01 level (1-tailed); HIRA = Hazard Identification and Risk Assessment

4.5 Establishment of Safety Performance Measurement Framework

4.5.1 Delineation of Safety Indicators and Determination of Weights of the Indicators

Prior to establishment of fuzzy inference system, a framework of safety performance measurement was established. Weights of indicators used for scoring of the safety factors were derived from multiplication of perceived importance ratings and perceived risk ratings of the respective safety indicators. Similarly, the weights of the safety factors were computed by multiplication of the mean perceived importance ratings and the mean perceived risk ratings of the safety factors.

Weights of safety factors are shown in **Figure 4.8** while weights of individual safety indicators are shown in **Table 4.15**. Upon further revision of the safety indicators and consultation with industrial practitioners, indicators measuring overlapping dimensions and lacking clarity were omitted or modified as described in **Appendix C** and **Table 4.15**. A final list with 63 indicators for safety performance measurement of offshore installations was yielded.

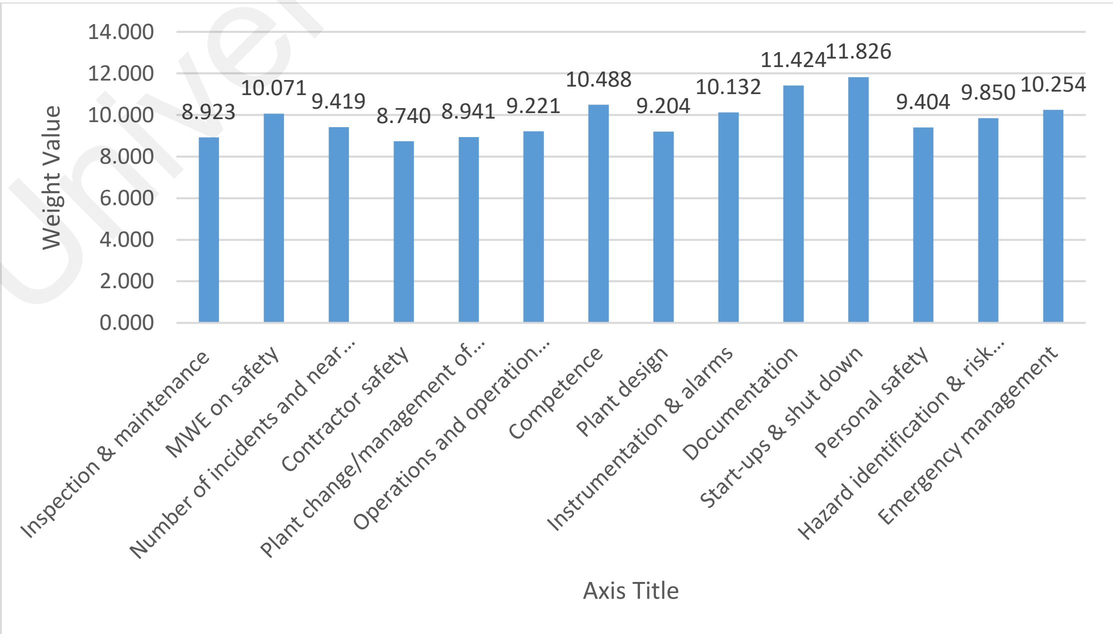


Figure 4.8: Weights of Safety Factors

Table 4.15: Safety Indicators, Weights and Scores for Various Compliance Status

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
	Safety Factor 1: Inspection & Maintenance			***114.300***	***76.200***	***38.100***
1	Number of safety critical plant/ equipment that performs within specification when inspected	10.017	Nil	30.052	20.035	10.017
2	Number of out of service equipment	7.476	Omitted due to similarity with Item 1. Measuring Item 1 enables Item 2 to be captured.	Omitted	Omitted	Omitted
3	Number of maintenance actions identified that are completed to the specified timescale	9.303	Nil	27.909	18.606	9.303
4	Number of hours of critical maintenance backlog	9.143	Nil	27.428	18.286	9.143
5	Number of failure in electrical equipment & units	8.003	Omitted due to potential with certain aspect of Item 1.	Omitted	Omitted	Omitted
6	Number of all leaks	9.637	Nil	28.911	19.274	9.637

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
	Safety Factor 2: Emergency Management			***92.260***	***61.507***	***30.753***
7	Number of elements of emergency procedure that fail to function to performance standard	9.996	Nil	29.989	19.992	9.996
8	Percent staff who take the correct action during emergency events	10.649	Nil	30.325	20.216	10.649
9	Number of emergency exercises on schedule	10.108	Nil	32.778	21.852	10.108
	Safety Factor 3: Management and Work			***120.912***	***80.608***	***40.304***
10	Percent inspection of work locations completed by manager/ supervisor	10.926	Nil	32.778	21.852	10.926
11	Percent management & work engagement suggestions implemented	9.194	Nil	27.583	18.388	9.194
12	Percent safety meetings not fully attended by staff intended	9.722	Nil	29.166	19.444	9.722
13	Number of barrier weakness including unsafe conditions identified from management & work engagement (MWE)	10.462	Nil	31.386	20.924	10.462

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
	Safety Factor 4: Number of Incident and Near Misses			***255.831***	***170.554***	***85.277***
14	Number of incidents and near misses attributable to inferior maintenance	9.378	Nil	28.134	18.756	9.378
15	Number of workplace incidents and near misses due to lack of technical understanding	9.138	This item is merged with Items 16, 17 and 18 as distinction between the items can be hard to make in data collection. **The highest weight of the four items, denoted by **, is adopted as the new weight.**	-	-	-
16	Number of workplace incidents and near misses due to inadequate training	9.938**	This item is merged with Items 15, 17 and 18 as distinction between the items can be hard to make in data collection.	29.813	19.876	9.938
17	Number of workplace incidents and near misses due to lack of skill in team	9.370	This item is merged with Items 15, 16 and 18 as distinction between the items can be hard to make in data collection.	-	-	-
18	Number of workplace incidents and near misses due to lack of experience	9.181	This item is merged with Items 15, 16 and 17 as distinction between the	-	-	-

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
			items can be hard to make in data collection.			
19	Number of incidents resulting from failure to manage change appropriately (e.g. procedural change without following policy)	9.402	Nil	28.206	18.804	9.402
20	Number of incidents involving loss of containment of hazardous material due to inadequate plant design	9.370	Nil	28.110	18.740	9.370
21	Number of incidents of plant breakdown due to inadequate plant design	8.309	Nil	24.928	16.619	8.309
22	Number of incidents during start-ups and shutdown	10.165	Nil	30.495	20.330	10.165
23	Number of incidents where plant/ equipment could be damaged due to failure to control high-risk maintenance	9.731	Nil	29.192	19.461	9.731
24	Number of incidents and near misses caused by contractors or visitors	9.287	Nil	27.862	18.574	9.287
25	Number of incidents where operational shortcuts were identified	9.697	Nil	29.091	19.394	9.697

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
	Safety Factor 5: Personal Safety			***225.806***	***150.538***	***75.269***
26	Number of exceedance of noise level beyond actionable level of 85dB(A)	9.233	Nil	27.699	18.466	9.233
27	Number of occupational disease cases reported	9.638	Nil	28.913	19.275	9.638
28	Number of occupational poisoning cases reported	9.618**	This item is merged with Item 29.	28.855	19.236	9.618
29	Number of food poisoning cases reported	9.255	This item is merged with Item 28 as occupational food poisoning is covered under occupational poisoning. The weight of Item 28, denoted by **, is adopted as the weight of the merged indicator.	-	-	-
30	Number of employees affected by chronic/ acute fatigue at work	8.835	Nil	26.504	17.669	8.835
31	Overtime working hours (over a fixed duration)	9.341	Nil	28.022	18.681	9.341
32	Number of extended shifts per person (over a fixed duration)	9.256	Nil	27.769	18.513	9.256

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
33	Number of exceedances of Permissible Exposure Limit for chemical hazardous to health	9.013	Nil	27.039	18.026	9.013
34	Number of medical surveillance showing exceeded threshold values	10.335	Nil	31.006	20.671	10.335
	Safety Factor 6: Contractor Safety			***52.446***	***34.964***	***17.482***
35	Percent contractors' act in accordance with company's policy	8.969	This is modified as 'Number of reported unsafe acts of contractors' for the ease of data collection.	26.906	17.937	8.969
36	Number of open/ unresolved contractors' safety suggestions	8.513	Nil	25.540	17.027	8.513
	Safety Factor 7: Plant Change/ Management of Changes			***160.707***	***107.138***	***53.569***
37	Number of times equipment or plant is below desired standard due to deficiencies in plant change	7.520	Nil	22.559	15.040	7.520
38	Number of hazard and operability (HAZOP) actions associated with plant change completed	7.754	Nil	23.262	15.508	7.754

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
39	Number of plant change actions undertaken where authorization was given before implementation	8.337	Nil	25.0124	16.675	8.337
40	Number of management of change (MOCs) in compliance with procedure	8.924	Nil	26.771	17.848	8.924
41	Number of emergency changes/ requests for emergency changes	10.237	Nil	30.711	20.474	10.237
42	Number of safe start-up following changes	10.797	Nil	32.392	21.594	10.797
	Safety Factor 8: Operation and Operating Procedure			***280.786***	***187.191***	***93.596***
43	Percent/ number of operation within design limits	9.281	Nil	27.842	18.561	9.281
44	Length of time plant is in production with safety critical plant or equipment in failed state	8.723	Nil	26.168	17.445	8.723
45	Total number of safety instrumentation and alarms activations reported by operation	8.916	Nil	26.747	17.831	8.916
46	Number of days with drilling/ completion activity	7.842	This is omitted due to a lack of relevance to safety.	Omitted	Omitted	Omitted
47	Number of days with workover	7.788	Nil	23.364	15.576	7.788

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
48	Number of trips, i.e. withdrawals of drill pipe	8.233	Nil	24.698	16.465	8.233
49	Number of exceedances of allowed burning time in restricted areas	9.574	Nil	28.722	19.148	9.574
50	Percent/ number of safety critical tasks for which a written operational procedure covers the correct scope	10.619	Nil	31.858	21.239	10.619
51	Percent/ number of clear and understandable procedures	9.668	Nil	29.004	19.336	9.668
52	Percent/ number of reviewed and revised procedures within the designated period	10.979	Nil	32.937	21.958	10.979
53	Number of PHA recommendations related to inadequate operating procedures	9.816	Nil	29.448	19.632	9.816
	Safety Factor 9: Competence			***94.361***	***62.908***	***31.454***
54	Number of experienced area operators	10.280	Nil	30.841	20.560	10.280
55	Percent/ number of time that asset integrity/ process safety critical positions have gone unstaffed	11.001	Nil	33.002	22.001	11.001

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
56	Number of individuals who completed a planned PSM (Process Safety Management) training	10.173	Nil	30.519	20.346	10.173
	Safety Factor 10: Hazard Identification & Risk Assessment			***88.683***	***59.122***	***29.561***
57	Number of completed hazard identification & risk assessment	10.050	Nil	30.149	20.100	10.050
58	Number of P&ID (Process & Instrument Diagram) corrections and other actions identified during process hazard analyses	9.548	Nil	28.645	19.097	9.548
59	Average number of hours per process & instrument diagram (P&ID) for conducting baseline & revalidation of PHA (process hazard analysis)	9.963	Nil	29.888	19.925	9.963
	Safety Factor 11: Plant Design			***83.091***	***55.395***	***27.697***
60	Percent/ number of safety critical equipment or components of plant which comply with current design standards or codes	9.157	Nil	27.472	18.315	9.157
61	Percent/ number of replacement of inferior components or systems with safer ones	10.606	Nil	31.817	21.212	10.606

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
62	Number of post-startup modifications required	7.934	Nil	23.802	15.868	7.934
	Safety Factor 12: Instrumentation & Alarms			***121.668***	***81.112***	***40.556***
63	Number of failure of safety critical instruments/ alarms, either in use or during testing	9.128	Nil	27.385	18.256	9.128
64	Number of safety instrumentation and alarms faults during tests	11.106	Nil	33.318	22.212	11.106
65	Number of safety critical instruments and alarms that activate at desired set point	9.696	Nil	29.088	19.392	9.696
66	Number of functional tests of safety critical instruments and alarms completed to schedule	10.626	Nil	31.877	21.252	10.626
	Safety Factor 13: Documentation			***68.552***	***45.702***	***22.851***
67	Number of facility related safety documents completed as per corporate and legal requirement	11.137	Nil	33.411	22.274	11.137
68	Number of facility related safety documents retained as per corporate and legal requirement	11.714	Nil	35.142	23.428	11.714

Item	Safety Indicators	Weight	Remarks	Score of Full Compliance	Score of Isolated Failure	Score of Non-compliance
	Safety Factor 14: Start-up			***70.976***	***47.318***	***23.659***
69	Number of deferred start-up & unplanned shutdown	11.422	Nil	34.267	22.845	11.422
70	Number of personnel trained on start-ups and shutdowns	12.236	Nil	36.709	24.473	12.236

4.5.2 Sensitivity Analysis of Safety Performance Scoring System

Sensitivity analysis examines the extent of changes in total safety scores with indicators of different weights and the type of weight that yields most notable changes in the total safety scores. **Figure 4.9** shows the total safety scores obtained by varying the compliance states of 10 safety indicators with highest weights and 10 safety indicators with lowest weight respectively, while the compliance state of other indicators remained constant. The total safety score should be the same when all the indicators assumed a 'compliant status'. Generally, altering the compliance states of indicators with higher weights yield a lower safety score than altering the compliance states of indicators with lower weights.

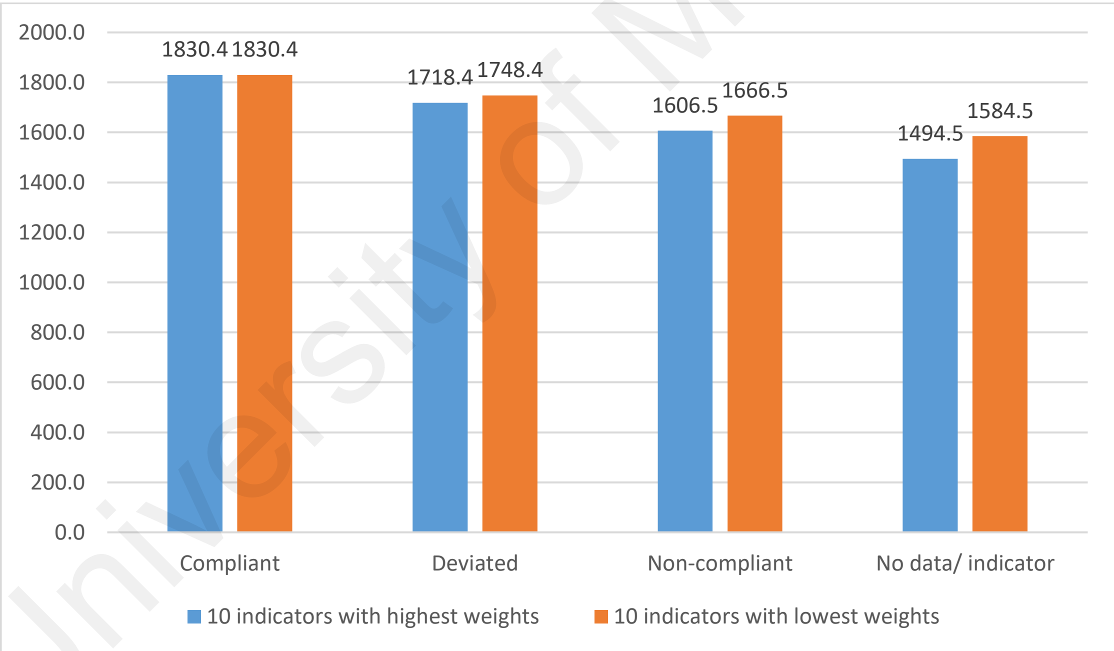


Figure 4.9: Effect of Varying Compliance States of 10 Indicators on the Total Safety Score

Sensitivity analysis of the total safety score was repeated by changing the compliance states of 20 safety indicators with highest weights and 20 safety indicators with lowest weight respectively, which yielded the results shown in **Figure 4.10**.

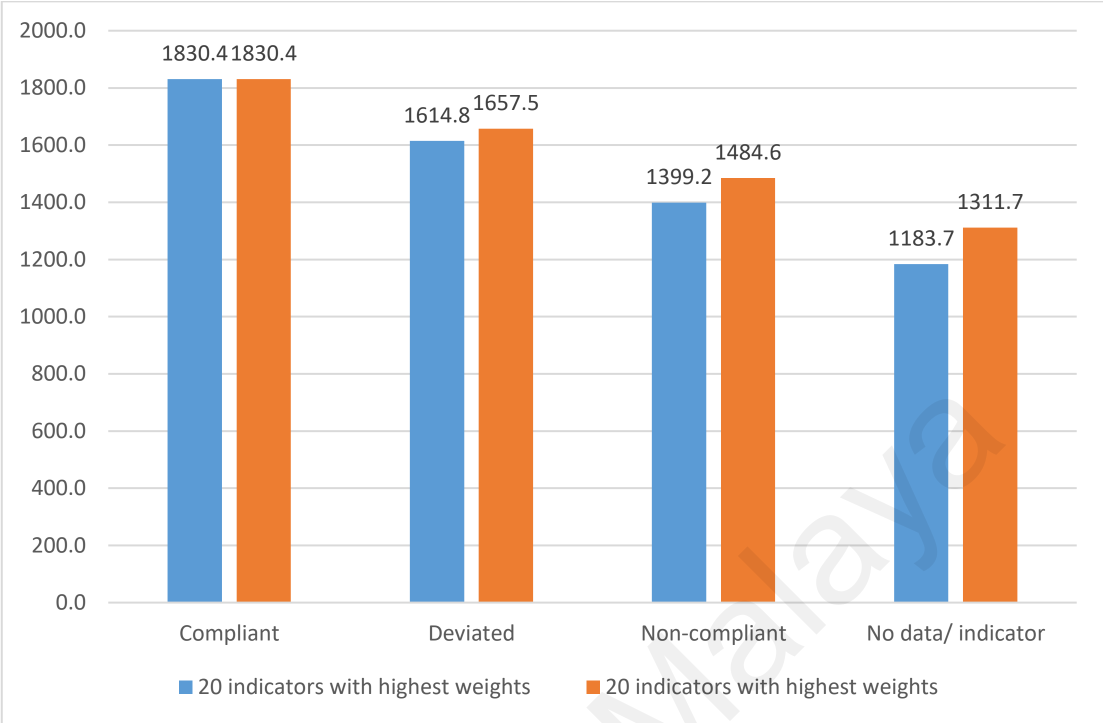


Figure 4.10: Effect of Varying Compliance States of 20 Indicators on the Total Safety Score

Reasonably, as the state of compliance for the indicators deteriorates from deviated to a total lack of data or indicators, the changes in the safety score becomes more pronounced. **Figure 4.11** compares the changes in safety scores by altering compliance states of 10 and 20 safety indicators with the highest and lowest weights successively.

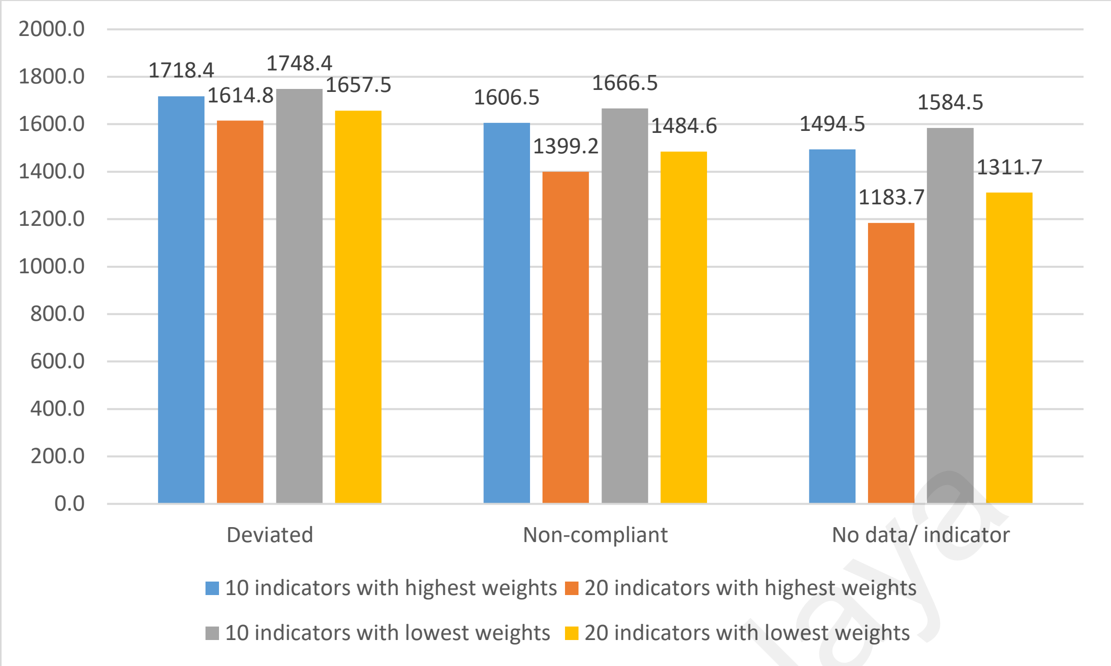


Figure 4.11: Comparison of Safety Scores based on Weights derived from Multiplication of Perceived Importance and Perceived Risk Ratings

Sensitivity analysis was also conducted for weights solely based on perceived importance ratings and perceived risk ratings of the safety indicators respectively for comparison. The results are shown in **Figure 4.12** and **Figure 4.13** below.

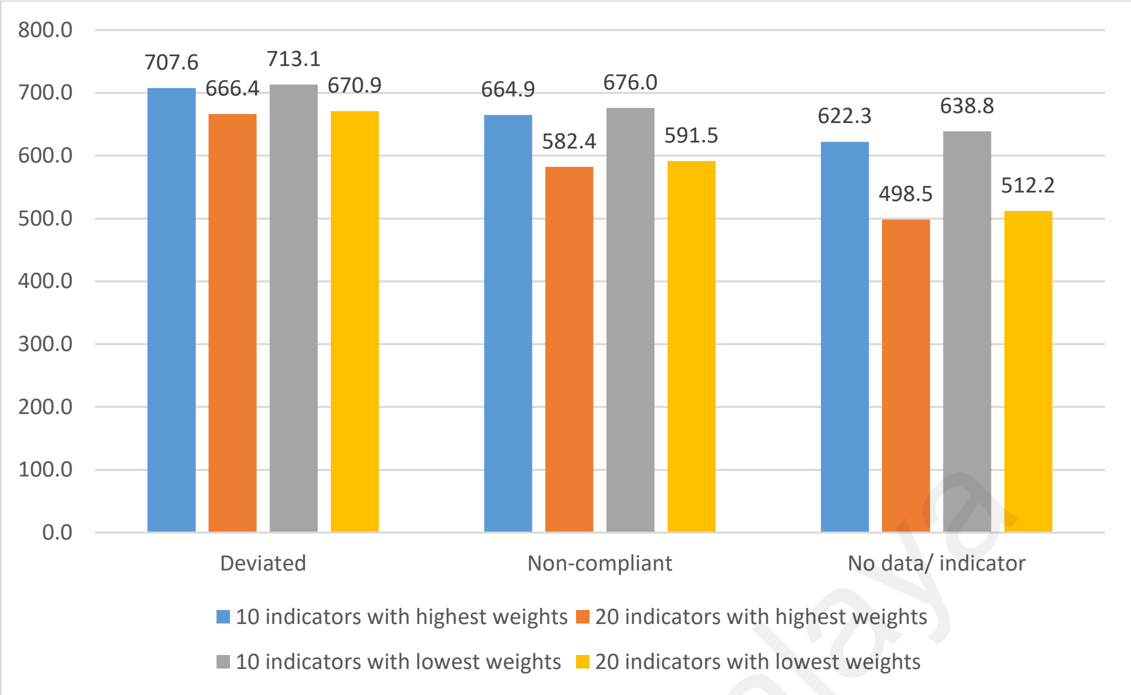


Figure 4.12: Comparison of Safety Scores based on Weights derived from Perceived Importance Ratings

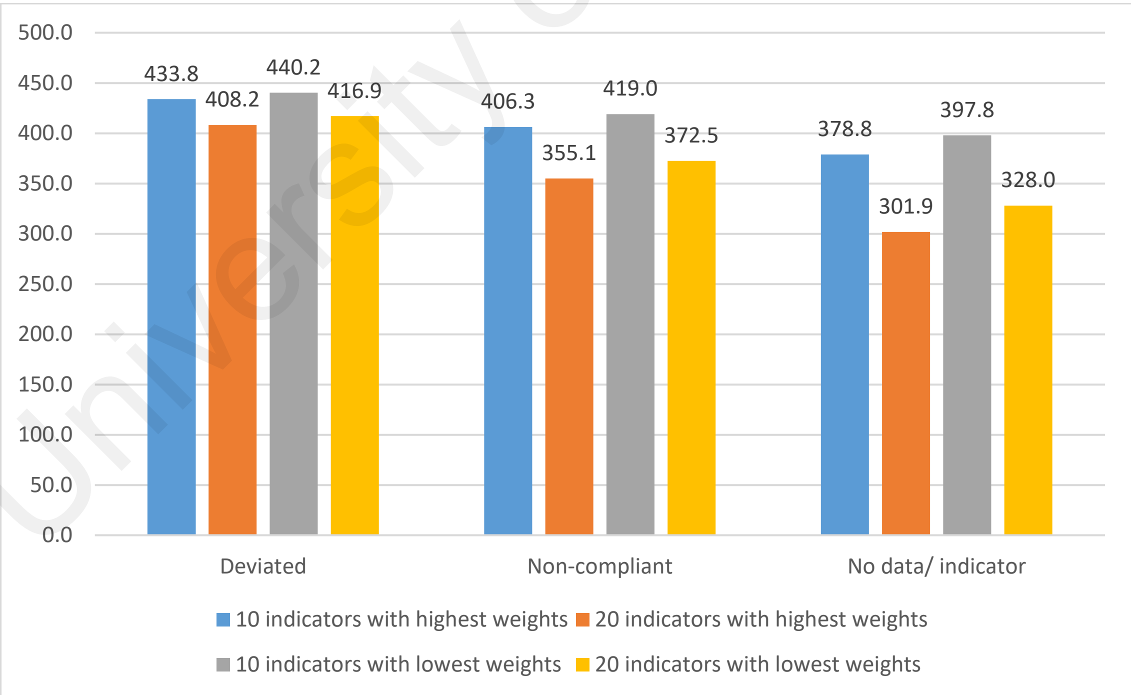


Figure 4.13: Comparison of Safety Scores based on Weights derived from Perceived Risk Ratings

Sensitivity index (SI) of **Figures 4.11**, **4.12** and **4.13** are shown in **Figures 4.14, 4.15** and **4.16 respectively**. Three parameters have been tested, i.e. weights, number of indicators and compliance states. With the maximum sensitivity index of 1, noticeable changes in sensitivity index can be observed by altering compliance states of different numbers of indicators with the highest and the lowest weights. A state of full compliance represents the maximum output of the system with a total safety score of 1830.4, thus, yielding an SI of 0. The SI calculation is based on **Equation 3.14**. At a fully compliance state, D_{min} is equal to D_{max} which is 1830.4, producing an SI of 0.

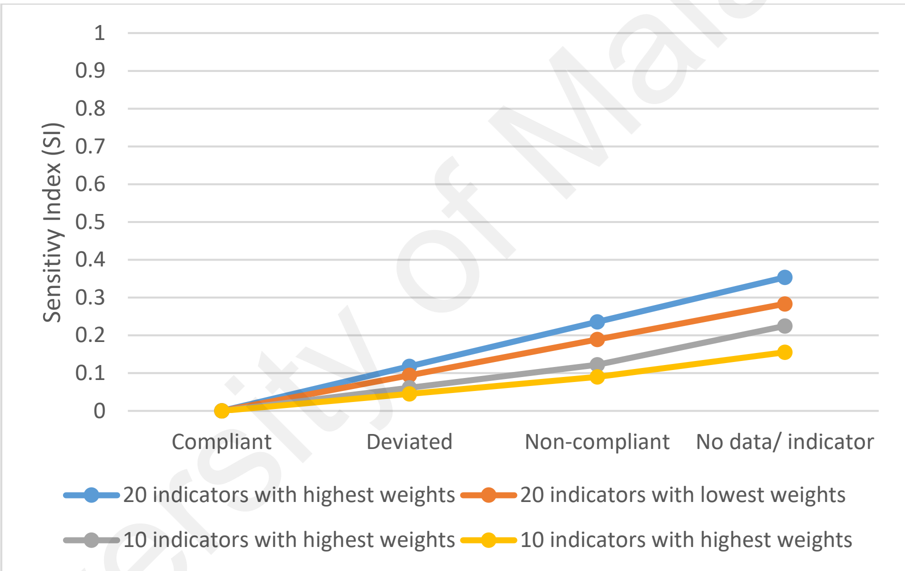


Figure 4.14: Sensitivity Index of Indicators based on Weights derived from Multiplication of Perceived Importance and Perceived Risk Ratings

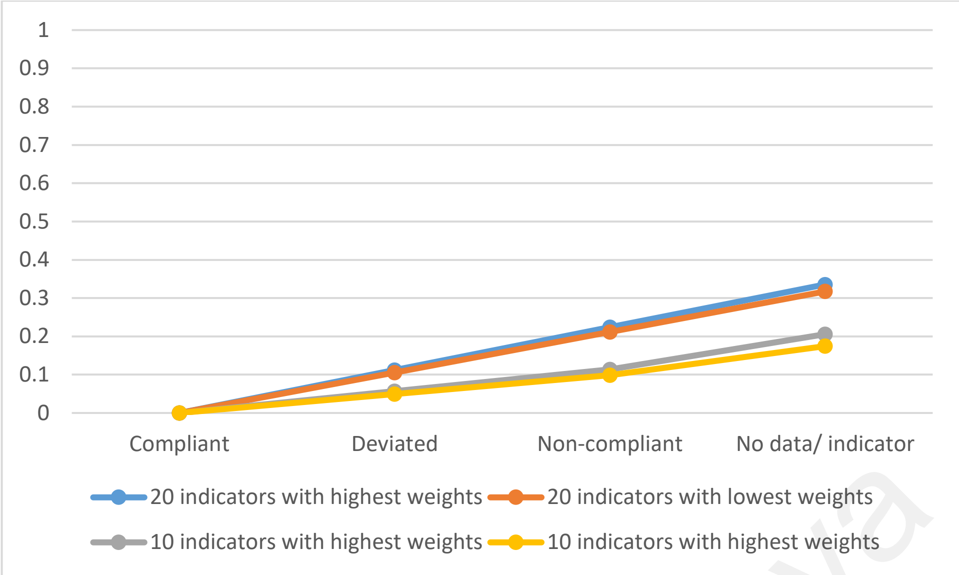


Figure 4.15: Sensitivity Index of Indicators based on Weights derived from Perceived Importance Ratings

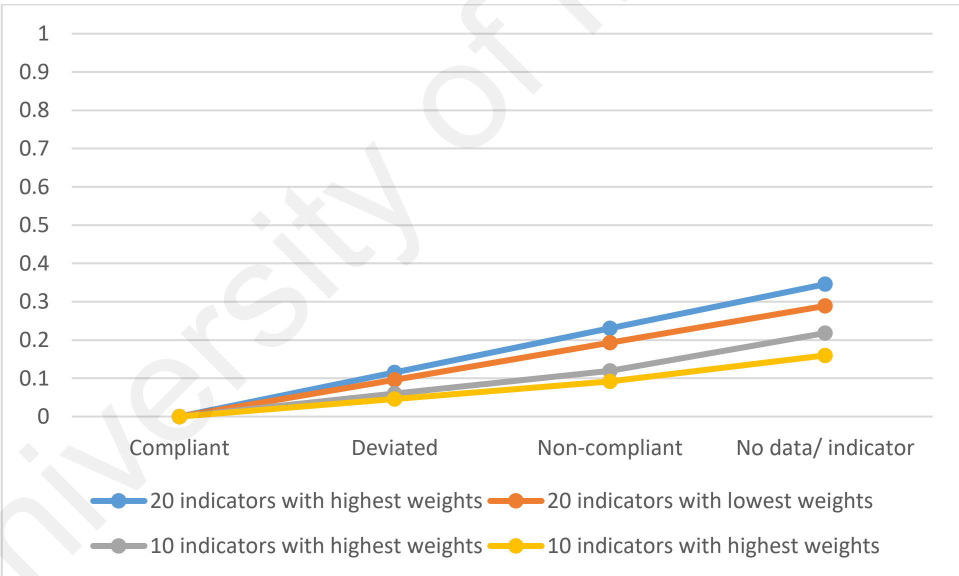


Figure 4.16: Sensitivity Index of Indicators based on Weights derived from Perceived Risk Ratings

SI of weights derived from multiplication of perceived importance and perceived risk ratings (**Figure 4.14**) are comparable with those derived solely from perceived risk ratings (**Figure 4.16**) though the former shows marginally greater sensitivity with more spaced out plots at all compliance statuses. Weights derived from perceived importance ratings are least sensitive with overlapping lines which are closely packed (**Figure 4.15**).

In all instances**,** changes in the compliance states of same sets of indicators lead to changes in the total safety score, with indicators of higher weights producing more changes than indicators with lower weights.

4.5.3 Testing of Fuzzy Inference System for Safety Performance Measurement

The fuzzy inference system was tested with the safety performance data for year 2016 obtained from ten offshore oil platforms located on the shallow waters of Miri, Malaysia. The score for each of the safety factors is shown in **Table 4.16**. Scores of safety factors are the sum of scores of safety indicators grouped under the respective safety factors. Scores of safety indicators were calculated by multiplying the respective indicator's weights with the compliance score of 0, 1, 2 or 3. The compliance score for each safety indicator was assigned by the industrial practitioners, based on comparison of the actual performance of the indicator against the target or performance standard set (Ratnayake, 2012). The scores were entered into the fuzzy inference system established as shown in **Figure 3.15**, **Chapter 3** (also see **Appendix F**).

Table 4.16 shows that Platform 2 was the best performing platform in terms of safety, outperforming the other platforms particularly in the area of management and work engagement, personal safety, operation and operating procedures as well as competence. All scores of safety factors calculated using the framework proposed (**Table 4.16**) fall between the maximum and middle scores (i.e. the score of full compliance and the score with all indicators in deviated state) (**Table 4.15**) of the respective safety factors with most of the scores above the mid-line of the range, except the scores of start-ups and shutdown for two platforms (Platforms 1 and 5) just slightly above the middle score. Score of inspection and maintenance of Platform 9 was the lowest of all platforms surveyed, though still above the middle score of 76.2. Platform 2 had the highest safety score of 1811 followed by Platform 4 and Platform 5 (**Table 4.16**). Platform 1 had the lowest safety score though it was still significantly higher than the middle score (refer **Table 4.16**).

Table 4.16: Scores of Safety Factors

Safety Factor	Platform									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Inspection and maintenance	104.7	104.7	104.7	104.7	95.0	94.7	114.3	114.3	85.5	114.3
Emergency management	92.3	92.3	82.3	82.3	92.3	82.3	81.6	81.6	81.6	92.3
Management and work engagement	101.3	120.9	120.9	120.9	110.5	91.5	100.7	101.3	100.7	100.8
Number of incidents and near misses	197.5	246.1	236.8	236.8	246.5	227.0	236.3	255.8	226.6	236.4
Personal safety	198.5	225.8	216.6	216.6	225.8	188.6	207.7	216.6	198.7	216.8
Contractor safety	52.4	52.4	52.4	52.4	52.4	43.5	43.9	52.4	52.4	43.5
Management of change	137.9	160.7	160.7	160.7	153.2	150.5	151.8	160.7	144.3	153.2
Operation and operating procedures	252.1	280.8	280.8	280.8	280.8	271.0	251.8	241.2	261.5	260.1
Competence	84.1	94.4	94.4	94.4	94.4	94.4	94.4	84.2	94.4	84.2
Hazard identification and risk assessment	88.7	88.7	88.7	88.7	88.7	88.7	88.7	58.8	88.7	88.7
Plant design	83.1	83.1	83.1	83.1	83.1	83.1	75.2	83.1	72.5	75.2
Instrumentation and alarm	121.7	121.7	121.7	121.7	121.7	110.6	121.7	110.6	91.7	121.7
Documentation	68.6	68.6	68.6	68.6	68.6	68.6	68.6	68.6	68.6	68.6
Start-ups and shutdown	48.1	71.0	59.6	71.0	48.1	59.6	59.6	71.0	71.0	59.6
Total Score	1630.8	1811.1	1771.1	1782.5	1761.0	1653.8	1696.1	1700.1	1638.2	1715.1

Figure 4.17 shows the performance of the platforms studied in terms of their total safety scores. Referring to **Table 4.17**, number of incident and near misses had the largest range of variation with a variance of 249.0, followed by operation and operating procedures with a variance of 218.5. All the platforms had uniform score for documentation indicating that documentation is generally an established practice, hence full compliance. Spreads of scores for plant design and contractor safety from the respective means were low, as indicated by the variances and standard deviations in **Table 4.17**.

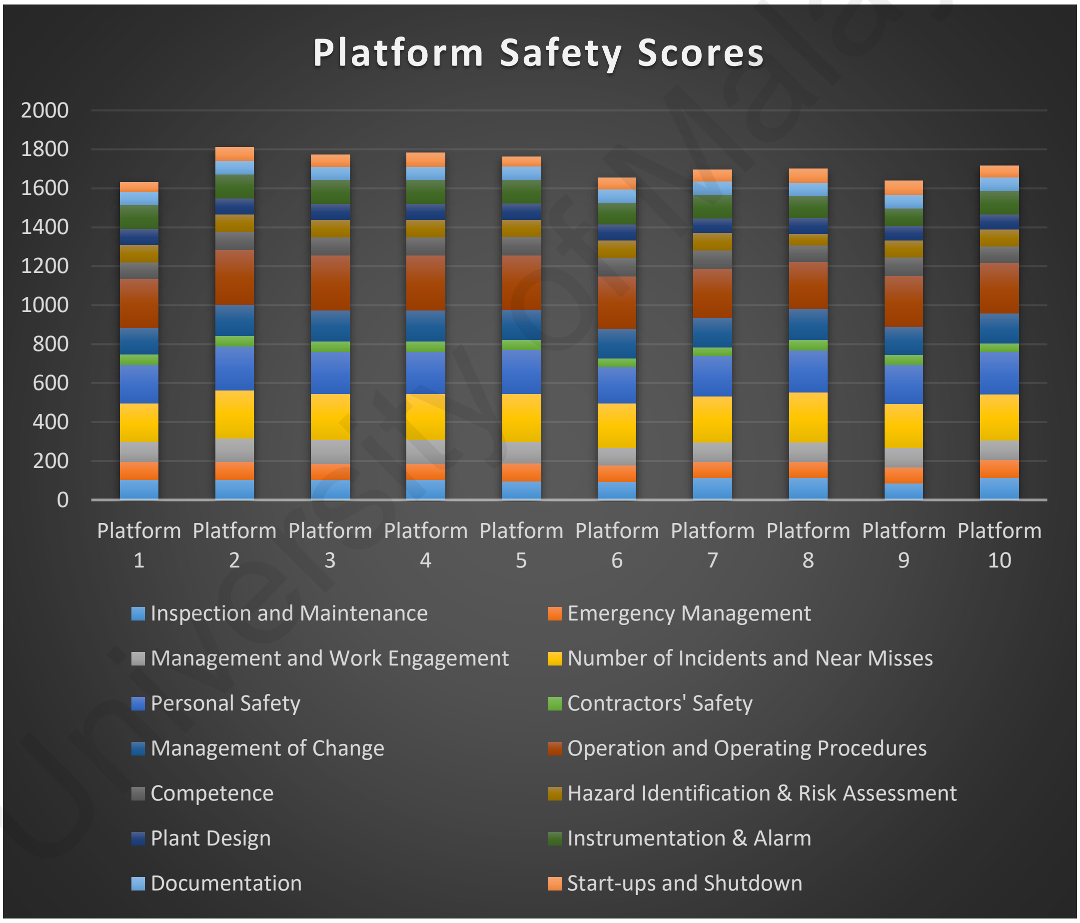


Figure 4.17: Platform Safety Scores for Year 2016

Table 4.17: Descriptive Statistics of Safety Factor Scores

Safety Factor	Range	Mean	Standard Deviation	Variance
Inspection and maintenance	28.8	103.7	9.6	92.1
Emergency management	10.7	86.1	5.3	28.5
Management and work engagement	29.4	106.9	10.6	112.8
Number of incidents and near misses	58.3	234.6	15.8	249.0
Personal safety	37.2	211.2	12.4	153.8
Contractor safety	8.97	49.8	4.3	18.2
Management of change	22.8	153.4	7.8	60.9
Operation and operating procedures	39.6	266.1	14.8	218.5
Competence	10.3	91.3	4.9	24.3
Hazard identification and risk assessment	29.9	85.7	9.5	89.3
Plant design	10.6	80.4	4.3	18.7
Instrumentation and alarm	29.9	116.5	9.8	96.7
Documentation	0.0	68.6	0.0	0.0
Start-ups and shutdown	22.8	61.8	9.0	81.1

Testing results of three cases of membership function of the fuzzy inference system on 10 platforms and 15 scenarios are shown in **Table 4.18** and **Table 4.19** respectively.

Table 4.18: Output of the Fuzzy Inference System on the Platforms Tested

		Output with membership function and defuzzification as follows:				
		Triangular (A) + CoA	**Trapezoidal (B) + CoA**	**Triangular & Trapezoidal (C) + CoA**	**Triangular & Trapezoidal (C) + MoM**	**(C) + Non-overlapping Output MFs + CoA**
Platform 1	Linguistic Output[1]	Slightly deviated	Compliant	Slightly deviated	Compliant	Slightly deviated
	Crisp Output[2]	75.4	91.2	75.4	92.0	77.3
Platform 2	Linguistic Output	Compliant	Compliant	Compliant	Compliant	Compliant
	Crisp Output	91.5	92.0	91.5	97.0	93.3
Platform 3	Linguistic Output	Compliant	Compliant	Compliant	Compliant	Compliant
	Crisp Output	89.8	92.0	89.8	94.5	91.7
Platform 4	Linguistic Output	Compliant	Compliant	Compliant	Compliant	Compliant
	Crisp Output	90.4	92.0	90.4	96.0	92.2
Platform 5	Linguistic Output	Compliant	Compliant	Compliant	Compliant	Compliant
	Crisp Output	90.5	91.9	90.5	94.0	92.5
Platform 6	Linguistic Output	Slightly deviated	Compliant	Slightly deviated	Compliant	Slightly deviated
	Crisp Output	76.4	90.7	76.4	93.5	79.4
Platform 7	Linguistic Output	Compliant	Compliant	Compliant	Compliant	Compliant
	Crisp Output	90.5	92.0	90.5	94.0	92.5
Platform 8	Linguistic Output	Compliant	Compliant	Compliant	Compliant	Compliant
	Crisp Output	90.6	92.0	90.6	94.0	92.5

		Output with membership function and defuzzification as follows:				
		Triangular (A) + CoA	**Trapezoidal (B) + CoA**	**Triangular & Trapezoidal (C) + CoA**	**Triangular & Trapezoidal (C) + MoM**	**(C) + Non-overlapping Output MFs + CoA**
Platform 9	Linguistic Output	Slightly deviated	Compliant	Slightly deviated	Compliant	Compliant
	Crisp Output	77.4	90.5	77.4	94.0	80.4
Platform 10	Linguistic Output	Compliant	Compliant	Compliant	Compliant	Compliant
	Crisp Output	90.5	92.0	90.5	94.0	92.5

[1] Linguistic output in a fuzzy inference system refers to fuzzy outputs defined in linguistic terms such as compliant, slightly deviated, highly deviated and non-compliance. Each linguistic term is characterized by an output membership function.

[2] Crisp output in a fuzzy inference system is generated by defuzzifying a fuzzy or linguistic output using a defuzzifier to yield a numerical value that corresponds with the linguistic output.

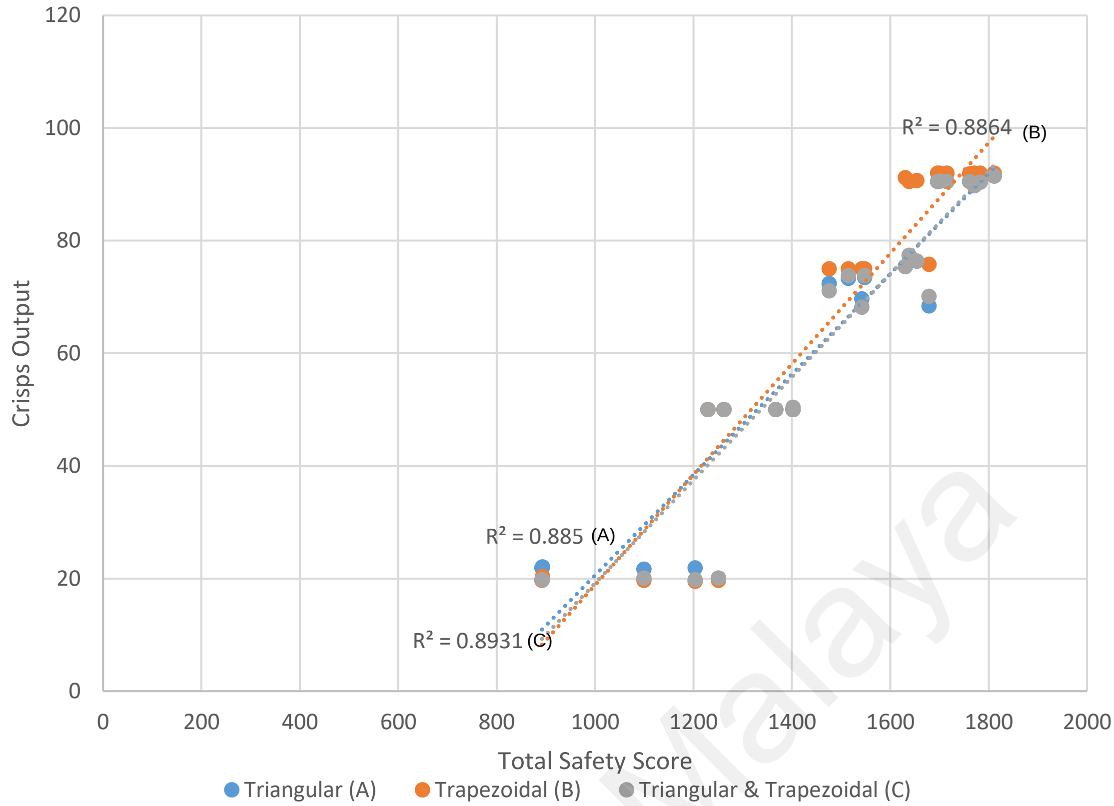
Table 4.19: Results of Scenario Testing

Scenario	Remark	Safety Score	Linguistic Output	Crisp Output for the Following Membership Functions				
				Triangular (A) + CoA	Trapezoidal (B) + CoA	Triangular & Trapezoidal (C) + CoA	Triangular & Trapezoidal (C) + MoM	(C) + Non-overlapping Output MFs + CoA
1	1 deviated and 1 non-compliant	1679	Slightly deviated	68.4	75.8	70.1	75.0	65.6
2	1 deviated and 2 non-compliant	1515	Slightly deviated	73.3	75.0	73.8	75.0	67.7
3	4 deviated	1542	Slightly deviated	69.7	75.0	68.2	75.0	59.0
4	2 deviated and 1 non-compliant	1548	Slightly deviated	73.5	75.0	73.8	75.0	67.7
5	3 deviated and 1 non-compliant	1476	Slightly deviated	72.4	75.0	71.1	75.0	66.3
6	2 deviated and 2 non-compliant	1402	Highly deviated	50.0	50.0	50.4	50.0	50.4
7	2 deviated and 3 non-compliant	1367	Highly deviated	50.0	50.0	50.0	50.0	50.0
8	4 deviated and 2 non-compliant	1402	Highly deviated	50.0	50.0	50.0	50.0	50.0

Scenario	Remark	Safety Score	Linguistic Output	Crisp Output for the Following Membership Functions				
				Triangular (A) + CoA	**Trapezoidal (B) + CoA**	**Triangular & Trapezoidal (C) + CoA**	**Triangular & Trapezoidal (C) + MoM**	**(C) + Non-overlapping Output MFs + CoA**
9	1 deviated and 5 non-compliant	1229	Highly deviated	50.0	50.0	50.0	50.0	50.0
10	2 deviated and 4 non-compliant	1262	Highly deviated	50.0	50.0	50.0	50.0	50.0
11	11 deviated and 3 non-compliant	1251	Non-compliant	20.1	19.7	20.1	14.5	16.9
12	9 non-compliant and 5 compliant	893	Non-compliant	22.1	20.4	19.8	14.0	16.7
13	6 deviated and 8 non-compliant	892	Non-compliant	21.9	19.7	19.8	14.0	16.7
14	6 compliant and 8 non-compliant	1203	Non-compliant	21.9	19.5	19.8	14.0	16.7
15	11 deviated and 3 non-compliant	1099	Non-compliant	21.7	19.7	20.1	14.5	16.9

Figure 4.18(a) and **Figure 4.18(b)** show plots of crisp outputs against total safety scores based on the results in **Table 4.18** and **Table 4.19**. While rule-setting of a fuzzy inference system permits non-linear mapping between the fuzzy input and output, a linear line was added to provide a general idea of how the crisp outputs corresponded to the total safety scores. The linear plot shows that Case C using both triangular and trapezoidal membership functions has the highest R-squared value, followed by Case B with trapezoidal membership function only and Case A with triangular membership function. R-squared value indicates the extent to which the data follows the fitted regression line. In this study, it is only used to describe the behavior of change of the fuzzy inference system's crisp outputs against the total safety scores.

Figure 4.18(a) depicts four plateaus of plots, each representing a state of compliance, i.e. non-compliant, highly deviated, slightly deviated and compliant, from the lowest to the highest. The plateaus indicate that the crisp outputs may not significantly differ with the varying degrees of a compliance state, for instance, the crisp outputs for non-compliant only fall within a very narrow range over a large range of total safety scores. **Figure 4.18(b)** also demonstrates similar plot pattern.



Note: All with CoA Defuzzification

Figure 4.18(a): A Plot of Safety Score against Crisp Outputs with CoA Defuzzification

Figure 4.18(b): A Plot of Safety Score against Crisp Outputs using CoA and MoM Defuzzification Methods for Case C only

Alternative set-up of the fuzzy inference system proposed was tested with the safety scores of the 10 platforms and Scenarios 1 to 5 as in **Table 4.19**. The alternative set-up gives a more stringent output that the un-partitioned set-up without intermediate models [**Tables 4.20(a) (b) (c)**]. Altering the extent of overlapping of the membership functions for intermediate outputs changes the ranges of score for the states of compliance, leading to notable difference in the final crisp outputs, hence the final states of compliance of the platforms and scenarios tested. Overlapping MFs in **Tables 4.20(b)** and **4.20(c)** confer more stringent results than non-overlapping MFs in **Table 4.20(a)**.

Table 4.20(a): Output of Alternative Set-up of Fuzzy Inference System

Platform	Output (with non-overlapping MFs for intermediate outputs)				
	Intermediate 1	Intermediate 2	Intermediate 3	Integrated Final	Linguistic
Platform 1	75.1	70.2	39.4	47.5	Highly deviated
Platform 2	90.2	87.8	86.2	90.7	Compliant
Platform 3	83.7	75.8	70.9	88.0	Compliant
Platform 4	83.7	75.8	86.2	88.9	Compliant
Platform 5	90.1	73.4	55.9	75.0	Slightly deviated
Platform 6	74.8	46.9	70.9	75.0	Slightly deviated
Platform 7	77.3	51.6	70.9	75.0	Slightly deviated
Platform 8	88.5	51.8	74.5	75.0	Slightly deviated
Platform 9	75.8	51.6	64.2	47.7	Highly deviated
Platform 10	81.8	69.9	53.1	47.5	Highly deviated
Scenario 1	86.6	47.6	72.8	75.0	Slightly deviated
Scenario 2	55.7	47.6	72.8	47.6	Highly deviated
Scenario 3	55.0	47.7	72.8	47.6	Highly deviated
Scenario 4	50.0	47.7	72.8	47.6	Highly deviated
Scenario 5	16.7	47.7	72.8	47.6	Highly deviated

Table 4.20(b): Output of Alternative Set-up of Fuzzy Inference System

Platform	Output (with highly overlapping MFs for intermediate outputs)				
	Intermediate 1	Intermediate 2	Intermediate 3	Integrated Final	Linguistic
Platform 1	75.3	71.0	43.7	46.5	Highly deviated
Platform 2	86.8	85.0	84.1	91	Compliant
Platform 3	82.7	76.1	71.7	66.9	Slightly deviated
Platform 4	82.7	76.1	71.7	80.7	Slightly deviated
Platform 5	86.7	73.8	59.9	61.1	Highly deviated
Platform 6	75	48.8	71.7	49.4	Highly deviated
Platform 7	77.2	53.3	71.7	53	Highly deviated
Platform 8	85	53.5	75	63.1	Slightly deviated
Platform 9	76	53.3	65.7	46.8	Highly deviated
Platform 10	80.7	70.8	54.8	57.3	Highly deviated
Scenario 1	84.7	53.3	73.5	60.6	Slightly deviated
Scenario 2	60.4	53.3	73.5	40.2	Highly deviated
Scenario 3	60	53.3	73.5	39.6	Highly deviated
Scenario 4	50	53.3	73.5	36.6	Highly deviated
Scenario 5	23	53.3	73.5	35.5	Highly deviated

Table 4.20(c): Output of Alternative Set-up of Fuzzy Inference System

Platform	Output (with low overlapping of MFs for intermediate outputs)				
	Intermediate 1	Intermediate 2	Intermediate 3	Integrated Final	Linguistic
Platform 1	74.6	70.1	43.7	33.5	Highly deviated
Platform 2	91.6	88.9	86.9	90.4	Compliant
Platform 3	83.7	75.3	70.8	48.8	Highly deviated
Platform 4	83.7	75.3	86.9	75.0	Slightly deviated
Platform 5	91.8	73.0	59.9	47.9	Highly deviated
Platform 6	74.4	48.4	70.8	44.3	Highly deviated
Platform 7	76.9	51.8	70.8	47.7	Highly deviated
Platform 8	90.1	51.9	74	47.8	Highly deviated
Platform 9	75.3	51.8	65.5	47.8	Highly deviated
Platform 10	81.8	69.9	53.1	47.8	Highly deviated
Scenario 1	87.1	53.3	71.6	48	Slightly deviated
Scenario 2	60.4	53.3	71.6	48	Slightly deviated
Scenario 3	60	53.3	71.6	48	Slightly deviated
Scenario 4	50	53.3	71.6	48	Slightly deviated
Scenario 5	19.8	53.3	71.6	48	Slightly deviated

A plot of crisp outputs of intermediate 1 against its safety scores shows that crisp outputs increase with safety scores though not in a perfectly linear manner [**Figures 4.19(a) (b) (c)**]. **Figures 4.20(a) (b) (c)**, however, show that the crisp outputs of intermediate 2 plateau between the safety score range of 200 to 300 after which there is a sharp increase. Crisp outputs of intermediate 3 demonstrate a generally increasing trend with the safety scores [**Figures 4.21(a) (b) (c)**].

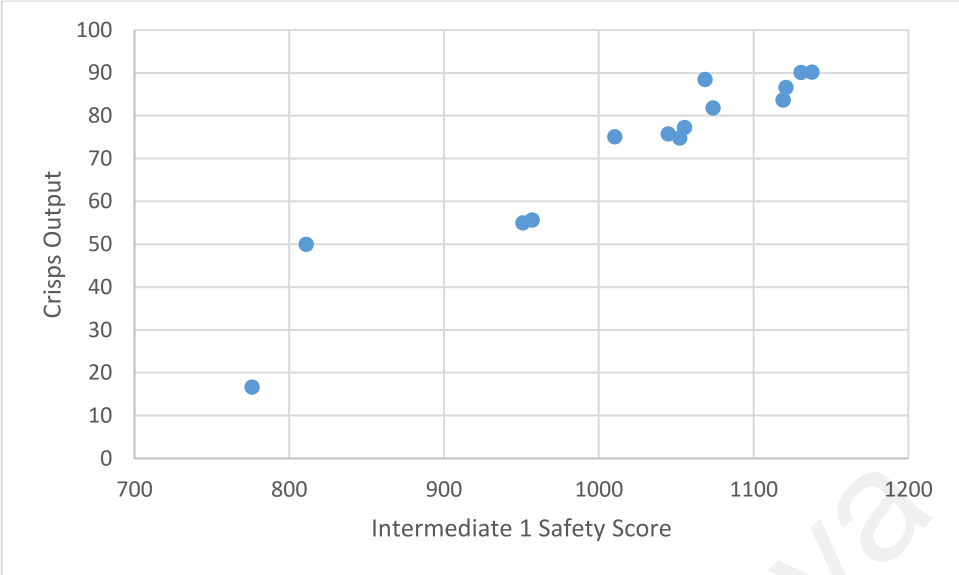


Figure 4.19(a): Crisp Output versus Safety Score for Intermediate 1 (Non-overlapping MFs)

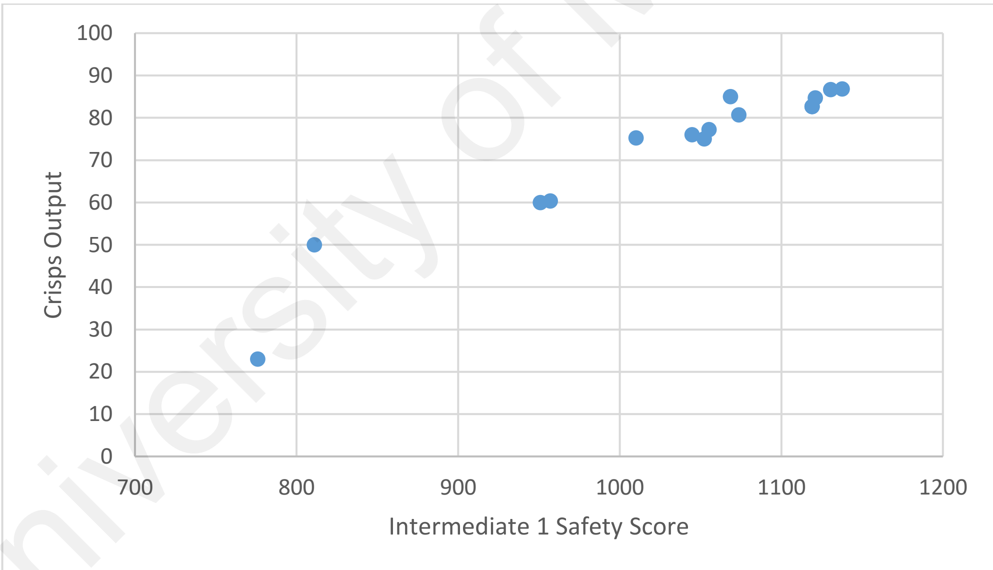


Figure 4.19(b): Crisp Output versus Safety Score for Intermediate 1 (Highly Overlapping MFs)

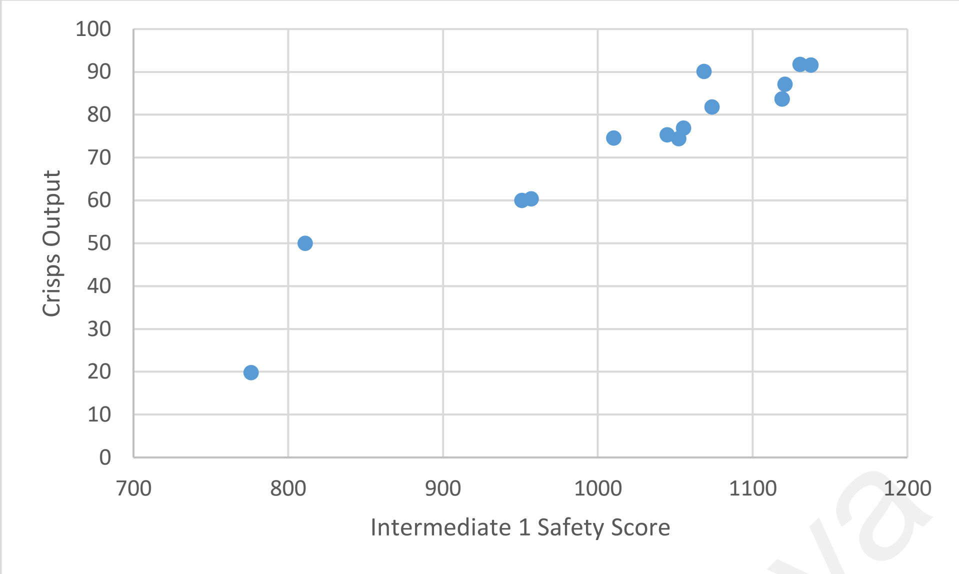


Figure 4.19(c): Crisp Output versus Safety Score for Intermediate 1 (Low Overlapping of MFs)

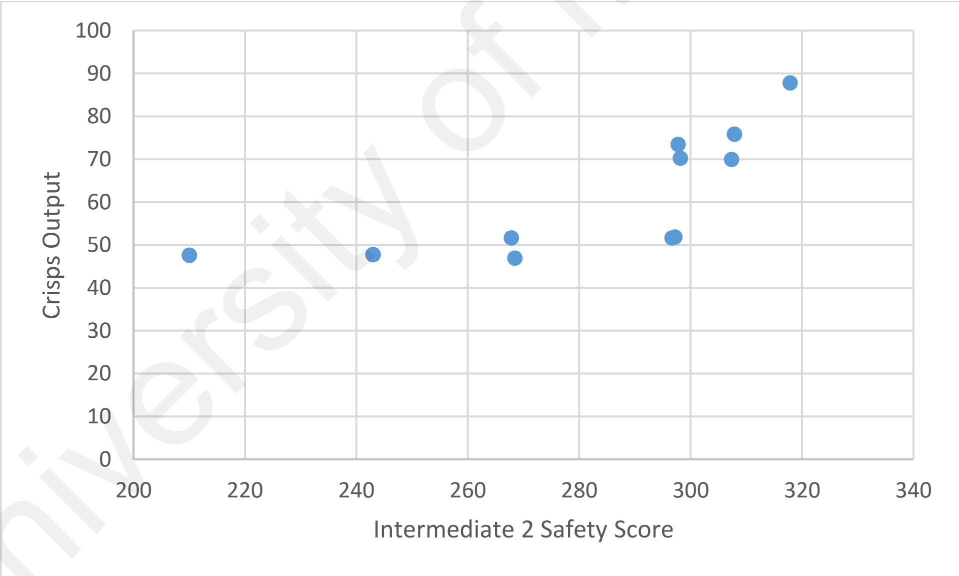


Figure 4.20(a): Crisp Output versus Safety Score for Intermediate 2 (Non-overlapping MFs)

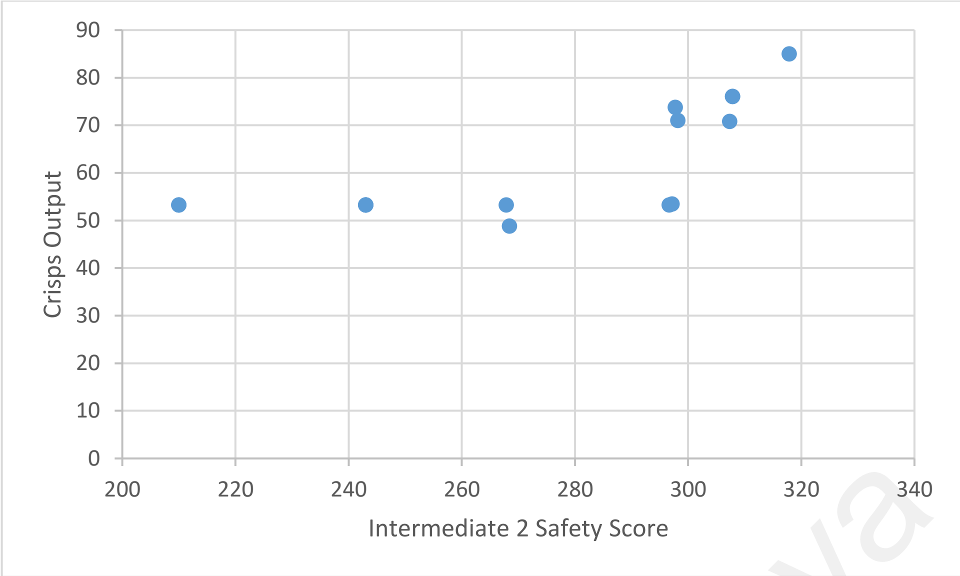


Figure 4.20(b): Crisp Output versus Safety Score for Intermediate 2 (Highly Overlapping MFs)

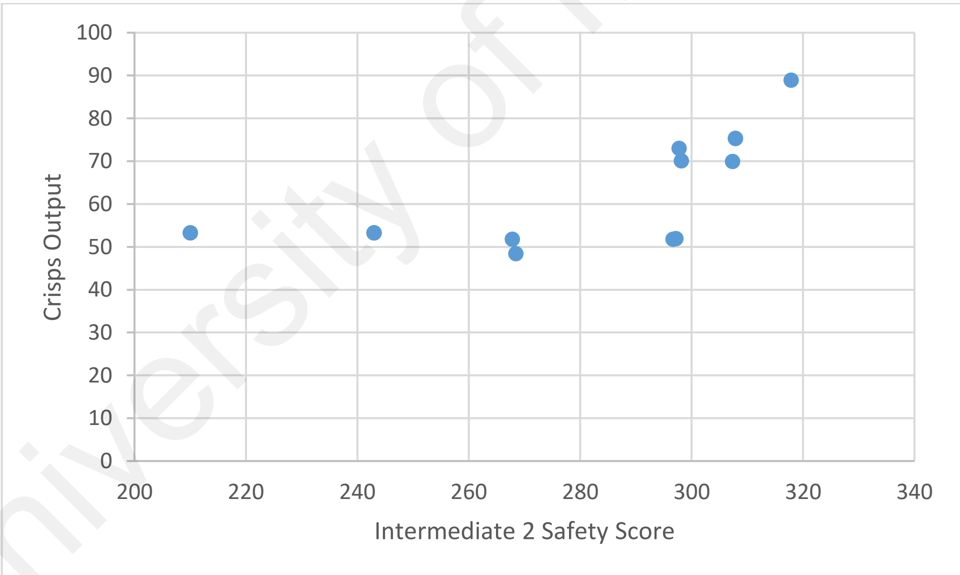


Figure 4.20(c): Crisp Output versus Safety Score for Intermediate 2 (Low Overlapping of MFs)

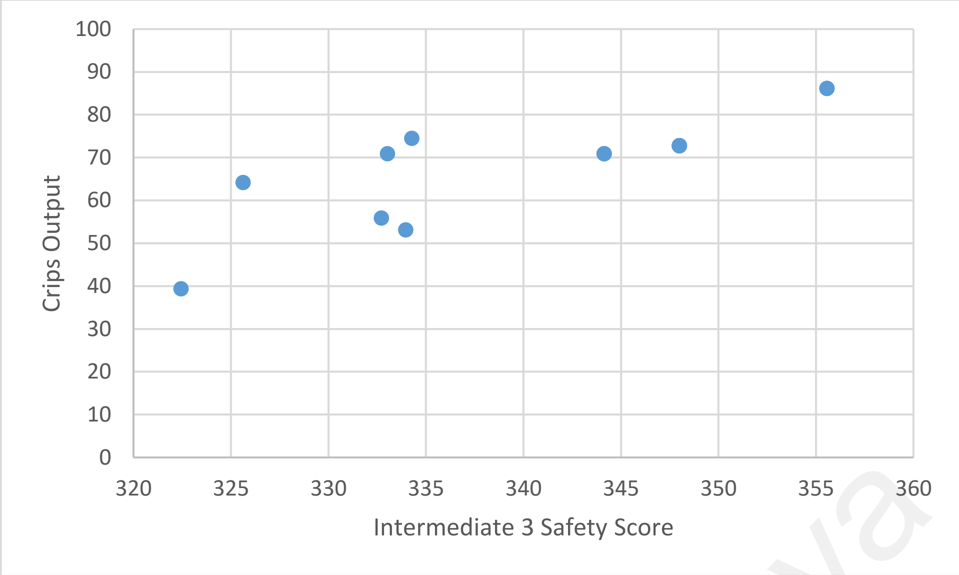


Figure 4.21(a): Crisp Output versus Safety Score for Intermediate 3 (Non-overlapping MFs)

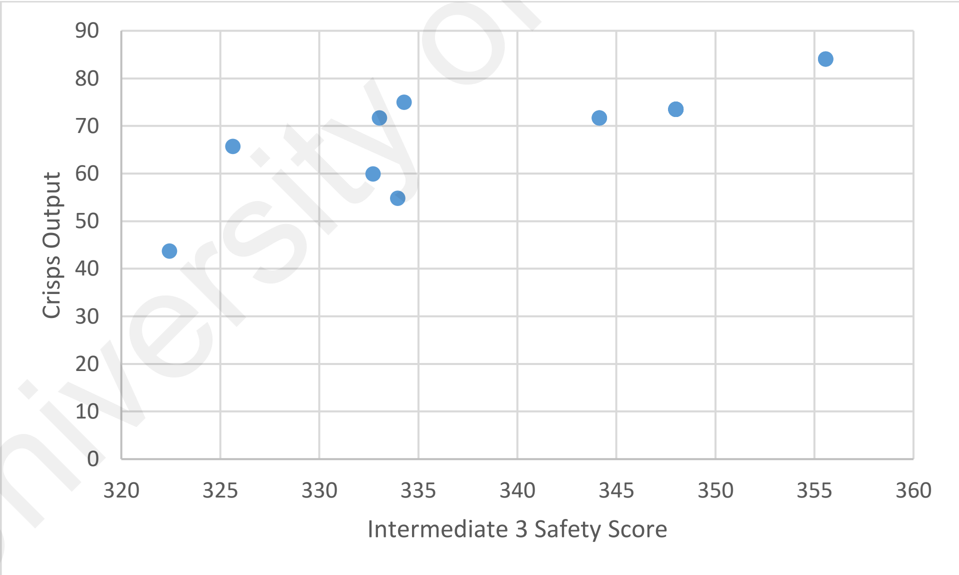


Figure 4.21(b): Crisp Output versus Safety Score for Intermediate 3 (Highly Overlapping MFs)

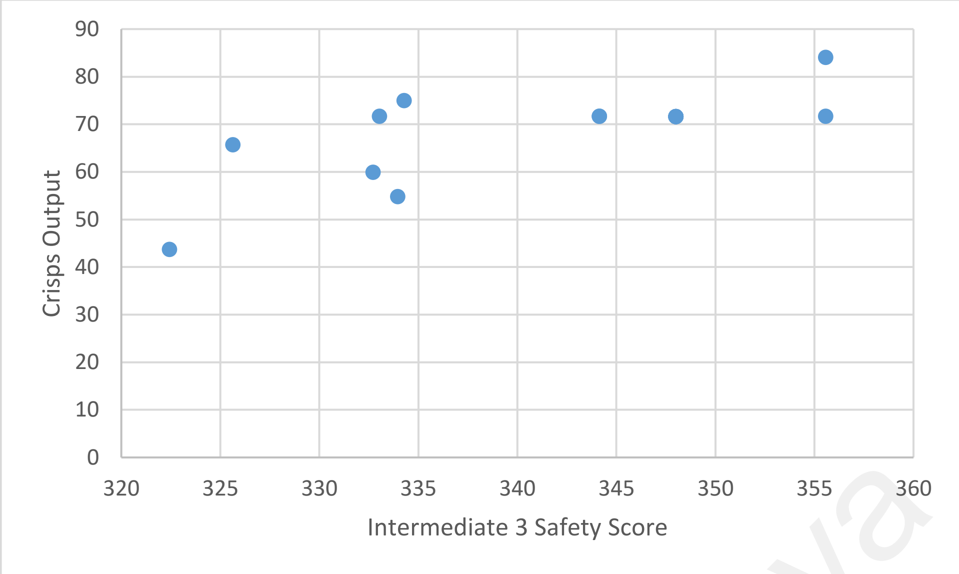


Figure 4.21(c): Crisp Output versus Safety Score for Intermediate 3 (Low Overlapping of MFs)

When crisp outputs of the integrated model were plotted against the total safety score, **Figures 4.22(a)** demonstrates a plot pattern similar to **Figure 4.18(a)** with plateaus of plots scattered across overlapping ranges of total safety score. Each plateau corresponds to a compliance state, i.e. the lowest being highly deviated, followed by slightly deviated and compliant at the top. A narrow range of safety score in **Figure 4.22(a)** can yield 3 completely different compliance statuses of a platform. **Figure 4.22(b)** shows a more consistent increase of crisp outputs with total safety score, though similarly, crisp outputs spread out widely over a narrow range of safety score. **Figure 4.22(c)** shows a single obvious plateau of crisp outputs over a range of total safety scores indicating that the crisp outputs lack sensitivity to the change in the total safety scores.

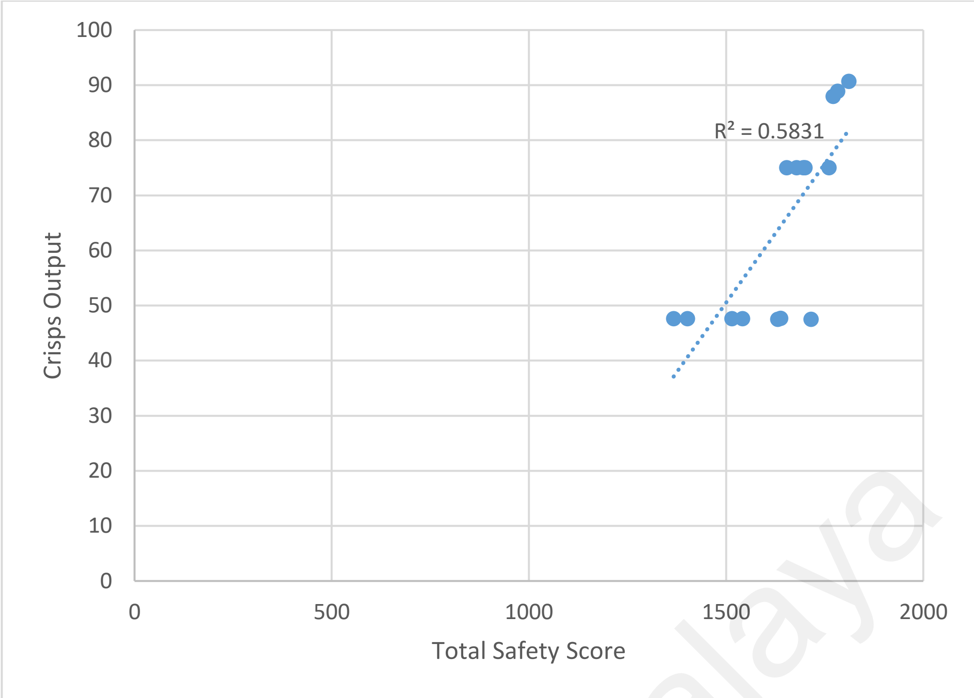


Figure 4.22(a): Crisp Output of Integrated Model versus Total Safety Score (Non-overlapping MFs)

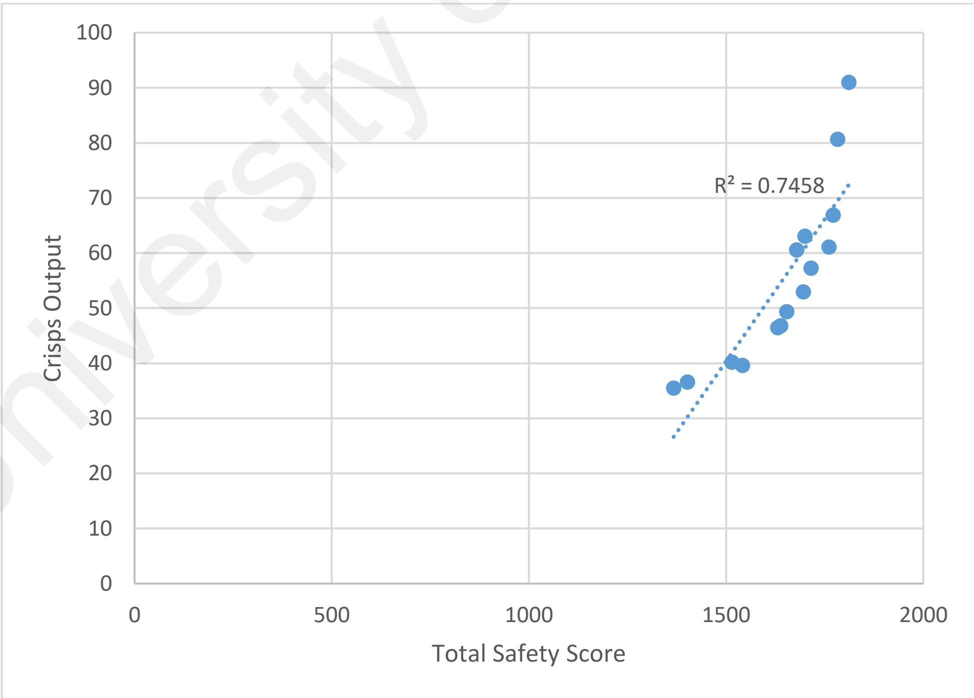


Figure 4.22(b): Crisp Output of Integrated Model versus Total Safety Score (Highly Overlapping MFs)

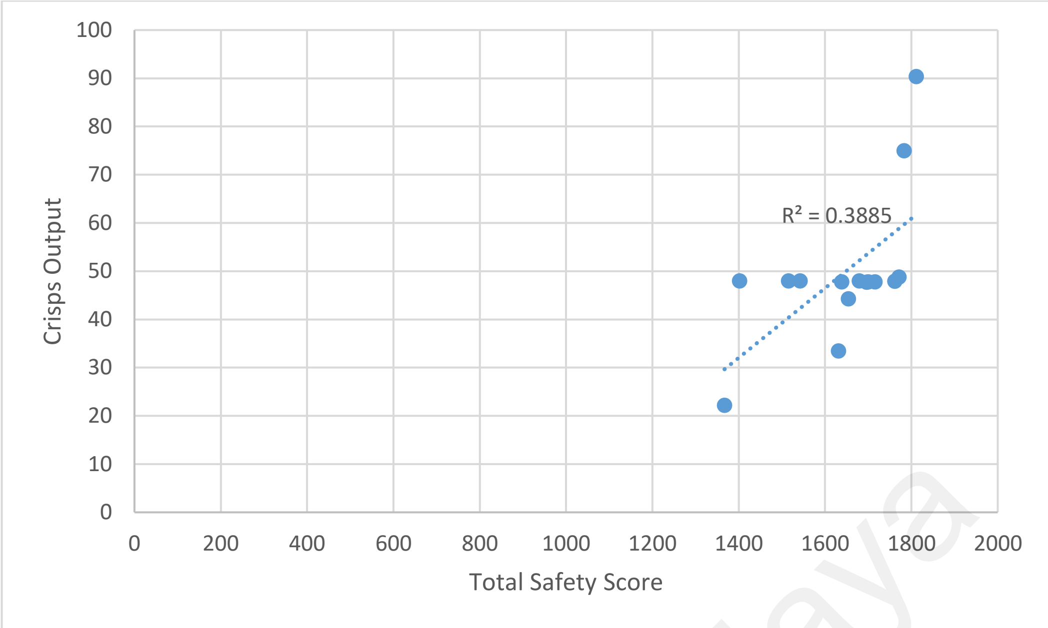


Figure 4.22(c): Crisp Output of Integrated Model versus Total Safety Score (Low Overlapping of MFs)

4.6 Validation of Safety Performance Measurement Framework

Actual performance of offshore oil and gas platforms is commonly captured in lagging indicators, particularly in terms of fatality and injuries (Morrow et al., 2014). **Table 4.21** shows the actual lagging performance of the platforms. There was no fatality reported on all the platforms in 2016. Platforms 1, 6 and 9 reported a total recordable injury rate more than 2, higher than the other platforms. Platform 8 recorded the highest lost time injury rate while Platform 1 had the highest reported near-misses.

Table 4.21: Actual Safety Data of Offshore Oil and Gas Platforms for Year 2016

Indicator	Platform									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Fatality	0	0	0	0	0	0	0	0	0	0
Fatal incident rate	0	0	0	0	0	0	0	0	0	0
Total recordable incident rate	2.43	1.21	1.69	1.71	1.75	2.26	1.88	1.84	2.37	1.92
Lost time injury rate	0.38	0.22	0.21	0.35	0.19	0.47	0.25	1.07	0.55	0.33
Reported near-misses	13	5	8	7	7	10	8	2	9	6

Table 4.22 shows correlation analysis between scores of the safety factors and the actual lagging performance of the platforms. Total recordable incident rate significantly and negatively correlated with MWE, number of incidents and near misses, personal safety and management of change. Lost time injury rate demonstrated significant negative correlation with the scores of operation and operating procedures, hazard identification and risk assessment, as well as instrumentation and alarm. Near misses, however, negatively correlated with number of incident and near misses, personal safety, management of change, hazard identification and risk assessment, as well as start-ups and shutdown. Significant positive correlation can be observed between near misses and total recordable incident rate.

Table 4.23 summarizes the correlations between the safety factors from Pearson correlation of perceived importance ratings, hierarchical clustering of perceived importance and perceived risk ratings as well as Pearson correlation of actual safety performance results. Results of Pearson correlation and hierarchical clustering based on perceived importance are in good agreement. Correlations from hierarchical clustering of safety factors based on perceived risk ratings also agree largely with those of perceived importance ratings. The actual safety performance data of only 10 platforms were collected. Though a larger sample size is preferred for correlation analysis, the actual correlations of safety factors established show very high agreement with correlations based on perceived importance ratings. The actual performance also revealed new correlations, for instance, MWE on safety correlated with management of change.

Table 4.22: Correlations between Safety Factor Scores and Actual Platform Lagging Performance

	Ins	Emer	MWE	Incident	Personal	Con	Change	Ops	Com	HIRA	Design	Inst	Startup	TRIR	LTIR	NM
Ins	1	0.082	0.072	0.259	0.370	-0.285	0.384	-0.422	-0.531	-0.389	0.065	0.619	0.031	-0.368	0.124	-0.437
Emer	0.082	1	0.133	-0.169	0.385	0.081	-0.220	0.173	-0.344	0.293	0.161	0.476	-0.499	-0.192	-0.421	0.087
MWE	0.072	0.133	1	0.333	0.726	0.605	0.624	0.685	0.380	0.188	0.397	0.447	0.241	-0.766	-0.437	-0.278
Incident	0.259	-0.169	0.333	1	0.697	0.062	0.845	0.175	0.210	-0.473	0.094	0.063	0.466	-0.730	0.208	-0.926
Personal	0.370	0.385	0.726	0.697	1	0.381	0.692	0.360	0.033	-0.153	0.237	0.513	0.125	-0.861	-0.221	-0.693
Con	-0.285	0.081	0.605	0.062	0.381	1	0.137	0.231	0.054	-0.218	0.414	-0.102	0.175	-0.219	0.132	-0.117
Change	0.384	-0.220	0.624	0.845	0.692	0.137	1	0.391	0.248	-0.331	0.364	0.323	0.515	-0.849	0.047	-0.796
Ops	-0.422	0.173	0.685	0.175	0.360	0.231	0.391	1	0.698	0.592	0.363	0.274	-0.007	-0.499	-0.672	0.059
Com	-0.531	-0.344	0.380	0.210	0.033	0.054	0.248	0.698	1	0.507	-0.002	-0.107	0.178	-0.298	-0.501	0.112
HIRA	-0.389	0.293	0.188	-0.473	-0.153	-0.218	-0.331	0.592	0.507	1	-0.215	0.211	-0.356	0.063	-0.895	0.654
Design	0.065	0.161	0.397	0.094	0.237	0.414	0.364	0.363	-0.002	-0.215	1	0.469	-0.173	-0.338	0.020	-0.069
Inst	0.619	0.476	0.447	0.063	0.513	-0.102	0.323	0.274	-0.107	0.211	0.469	1	-0.438	-0.526	-0.543	-0.044
Startup	0.031	-0.499	0.241	0.466	0.125	0.175	0.515	-0.007	0.178	-0.356	-0.173	-0.438	1	-0.331	0.438	-0.572
TRIR	-0.368	-0.192	-0.766	-0.730	-0.861	-0.219	-0.849	-0.499	-0.298	0.063	-0.338	-0.526	-0.331	1	0.290	0.676
LTIR	0.124	-0.421	-0.437	0.208	-0.221	0.132	0.047	-0.672	-0.501	-0.895	0.020	-0.543	0.438	0.170	1	-0.413
NM	-0.437	0.087	-0.278	-0.926	-0.693	-0.117	-0.796	0.059	0.112	0.654	-0.069	-0.044	-0.572	0.676	-0.413	1

Ins: Inspection and maintenance
Emer: Emergency management
MWE: Management and work engagement
Incident: Number of incidents and near misses
Personal: Personal safety
Con: Contractor safety
Change: Management of change
Ops: Operation and operating procedures
Com: Competence

HIRA: Hazard identification and risk assessment
Design: Plant design
Inst: Instrumentation and alarm
Startup: Start-ups and shutdown
TRIR: Total Recordable Incident Rate
LTIR: Lost Time Injury Rate
NM: Near misses
Red: Correlation is significant at the 0.05 level (1-tailed)
Blue: Correlation is significant at the 0.01 level (1-tailed)

Table 4.23: Correlation Summary of Safety Factors

	Ins	MWE	Incident	Con	Change	Ops	Com	Design	Inst	Doc	Startup	Personal	HIRA	Emer
Ins		(PI)(HI)(HR)	(HR)			(PI)			(V)					(PI)(HI)(HR)
MWE	(PI)(HI)(HR)		(PI)(HR)	(PI)(V)	(V)	(PI)(V)		(PI)				(PI)(V)	(PI)	(PI)(HI)(HR)
Incident	(HR)	(PI)(HR)		(PI)(HI)	(PI)(HI)(V)	(PI)		(PI)(HI)		(PI)		(PI)(HI)(HR)(V)	(PI)	(HR)
Con		(PI)(V)	(PI)(HI)		(PI)(HI)	(PI)(HI)		(PI)(HI)(HR)	(PI)	(PI)		(PI)(HI)	(PI)(HI)	
Change		(V)	(PI)(HI)(V)	(PI)(HI)		(PI)(HI)(HR)		(PI)(HI)				(PI)(HI)(V)	(PI)(HI)	
Ops	(PI)	(PI)(V)	(PI)	(PI)(HI)	(PI)(HI)(HR)		(PI)(V)	(PI)(HI)	(PI)	(PI)		(PI)	(PI)(HI)(V)	
Com						(PI)(V)			(PI)	(PI)	(PI)	(PI)	(HR)	
Design		(PI)	(PI)	(PI)(HR)	(PI)(HI)	(PI)			(PI)(HR)	(PI)		(PI)	(PI)	
Inst	(V)			(PI)		(PI)	(PI)	(PI)(HR)		(PI)(HI)	(PI)	(PI)		
Doc			(PI)	(PI)		(PI)	(PI)	(PI)	(PI)(HI)		(PI)(HR)	(PI)	(PI)	
Startup							(PI)		(PI)	(PI)(HR)		(PI)		
Personal	(PI)	(PI)(V)	(PI)(HI)(HR)(V)	(PI)(HI)	(PI)(HI)(V)	(PI)	(PI)	(PI)(HI)	(PI)	(PI)	(PI)		(PI)	(PI)
HIRA		(PI)	(PI)	(PI)(HI)	(PI)(HI)	(PI)(HI)(V)	(HR)	(PI)(HI)		(PI)		(PI)		
Emer	(PI)(HI)(HR)	(PI)(HI)	(HR)									(PI)		

Note: Explanation of Abbreviations for Table 4.22

Ins: Inspection and maintenance
MWE: Management and work engagement
Incident: Number of incidents and near misses
Con: Contactor Safety
Change: Management of change
Ops: Operation and operating procedures
Com: Competence
HIRA: Hazard identification and risk assessment

Design: Plant design
Inst: Instrumentation and alarm
Doc: Documentation
Startup: Start-ups and shutdown
Emer: Emergency management
PI: Significant Pearson correlation of Perceived Importance
HI: Correlation based on Hierarchical Clustering of Perceived Importance
HR: Correlation based on Hierarchical Clustering of Perceived Risk
V: Significant Pearson correlation based on Validation with Actual Performance Data

Facility status report is one of the practices of an oil and gas company in Malaysia to monitor the overall 'safety' status of offshore oil and gas platforms. Oil and gas companies are generally protective over such reports due to corporate reasons. Presentation and contents of the facility status reports may vary between companies. Summaries of facility status reports of Platforms 2 and 3 were sourced for comparison with the safety performance measurement framework proposed, in order to validate the framework. Facility status report of Platform 2 for year 2016 showed compliance for all groups of safety critical elements (SCE) except process containment with a deviated status due to isolated failure in meeting the performance target (**Table 4.24**). Each SCE group consists of a list of SCEs which represent the barriers to prevent and contain accidents likely to occur on offshore platforms (Jager, 2013). Structural integrity for instance consists of subsea structures, topside/ surface structures, heavy lift cranes and mechanical handling, ballast systems, mooring systems and drilling systems (**Table 4.25**). Performance goal was set for each SCE as indicated in **Table 4.26** and was evaluated based on the underlying functional criteria. There are two types of performance goal, i.e. design performance standards and operations performance standards. Design performance standards specify the design features, capacity or loads of the safety critical elements while operational performance standards specify the operational envelops, conditions and efficiency the elements are expected to demonstrate (Jager, 2013). As the platforms studied have been in operation, operational performance standards are the major concerns.

Facility status report of Platform 2 shows good agreement with the results of the safety performance framework proposed. Based on the framework, all the safety scores of Platform 2 achieved the status of full compliance except inspection and maintenance, and number of incident and near misses. Under the category of inspection and maintenance, the indicator that was rated deviated was the number of all hydrocarbon leaks (**Table 4.16**), which correlates with the finding of its facility status report on process containment. Facility status of Platform 3 shows deviation of process contaminant, shutdown systems and emergency response in line with the findings in **Table 4.16**.

Table 4.24: Compliance of SCE Groups in Facility Status Report of Platforms 2 and 3

SCE Groups	Platform 2		Platform 3	
	Compliance Status	Remark	Compliance Status	Remark
Structure Integrity	Green	Compliant	Green	Compliant
Process Containment	Amber	Deviated*	Amber	Deviated*
Ignition Control System	Green	Compliant	Green	Compliant
Detection Systems	Green	Compliant	Green	Compliant
Protection Systems	Green	Compliant	Green	Compliant
Shutdown Systems	Green	Compliant	Amber	Deviated*
Emergency Response	Green	Compliant	Amber	Deviated*
Life Saving Systems	Green	Compliant	Green	Compliant
Non-SCE Items	Green	Compliant	Amber	Compliant
Competency Deviation	Green	Compliant	Green	Compliant
Standards	Green	Compliant	Green	Compliant

*Due to isolated failure. However, the performance still falls within acceptable zone below the corresponding performance target.

Table 4.25: Safety Critical Elements

SCE Group	Safety Critical Element
Structural Integrity	• Subsea structures • Topside/ surface structures • Heavy lift cranes and mechanical handling • Ballast systems • Mooring systems • Drilling systems
Process Containment	• Pressure vessels • Heat exchangers • Rotating equipment • Tanks • Piping systems • Pipelines • Relief system • Well containment • Fired heaters • Gas tight floor/ walls • Tanker loading • Helicopter refuel • Wireline equip • Oil-in-water control
Ignition Control System	• Heating ventilation and air conditioning (HVAC) for hazardous environment • HVAC for non-hazardous environment • Certified electrical equipment • Inert gas (cargo) • Earth bonding • Fuel gas purge • Inert gas blanket system • Miscellaneous ignition Control • Flare tip ignition
Detection Systems	• Fire and gas • H_2O in condensate
Protection Systems	• Deluge • Fire/ explosion protection • FW pumps • Firewater main • Passive fire protection • Gaseous fire protection system • Fine water system • Sprinklers • Power management • Fixed foam systems • Sand filters

SCE Group	Safety Critical Element
	• Chemical injection • Navigation aids • Collision avoidance
Shutdown System	• Emergency shutdown and depressurization systems • Depressurization systems • High-integrity pressure protection systems • Operational well isolation • Pipelines isolation valves • Process emergency shutdown valves • Drilling well control • Utility air
Emergency Response	• Temporary refuge/ muster areas • Escape/ evacuation routes • Emergency/ escape lighting • Communication system • Uninterruptible power supply • Helicopter facilities • Emergency power • Open hazardous drains • Open non-hazardous drains
Life Saving Systems	• Personal survival equipment • Rescue facilities • Lifeboats/ TEMPSC (Totally enclosed motor propelled survival craft) • Tertiary means of escape

Table 4.26: Example of Operational Performance Standards

SCE Group	Protection System			
SCE	Fire Water Pumps			
SCE Goal	Provision of adequate water to extinguish or contain, hence reduce impact of fire.			
Function no.	Functional criteria	Minimum assurance task	Assurance measure	Assurance value
1	Each fire pump shall operate as per its design specifications	Test performance of fire pump as per design pump curve to ensure delivery of largest firewater demand	Firewater discharge pressure Firewater flow rate	≥ pressure ≥ flow
2	Each fire pump shall be activated by initiation signals and run without interruption in the span of a defined emergency event	Each fire pump shall be activated by pressing: • Local panel pushbutton • Fire & Gas panel pushbutton • Fire main pressure switch A testing plan should be in place for equal testing of all start signals above.	Fire pump starts on demand	Yes/ No

An attempt was made to demonstrate practical application of the integrative framework via producing a preliminary design of safety performance measurement dashboard for offshore oil and gas platforms as below using Qlik Sense, a well-established software for dashboard development (Ilacqua et al., 2015). The preliminary design (**Figure 4.23**) depicts great potential of the framework to be integrated with dashboard in actual safety performance measurement of offshore platforms (**Figure 4.24**).

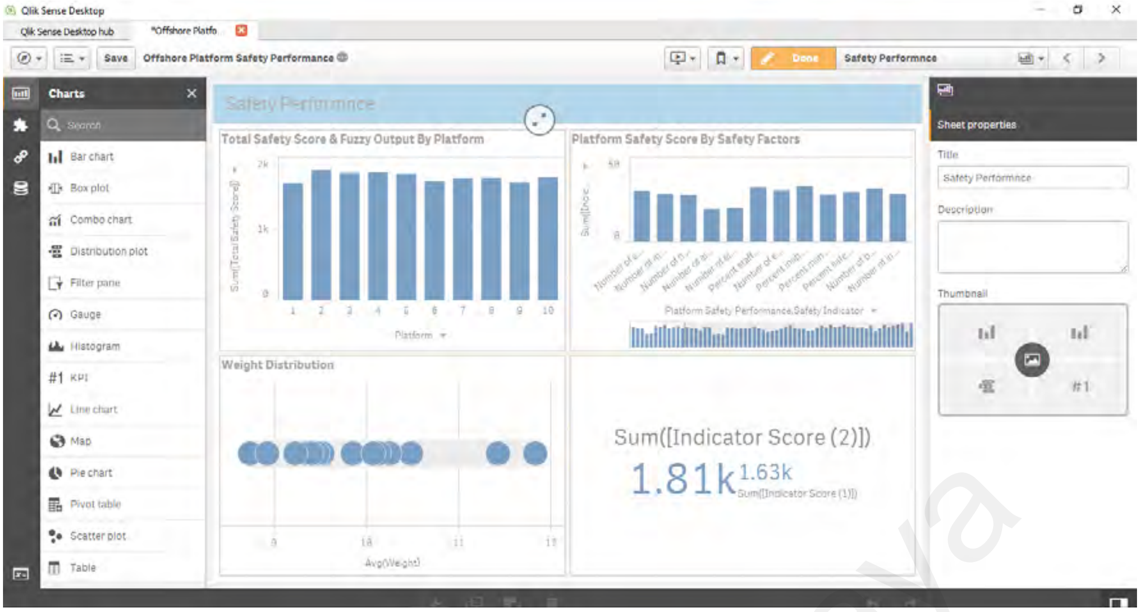


Figure 4.23: Designing Dashboard Presentation of Safety Performance Data

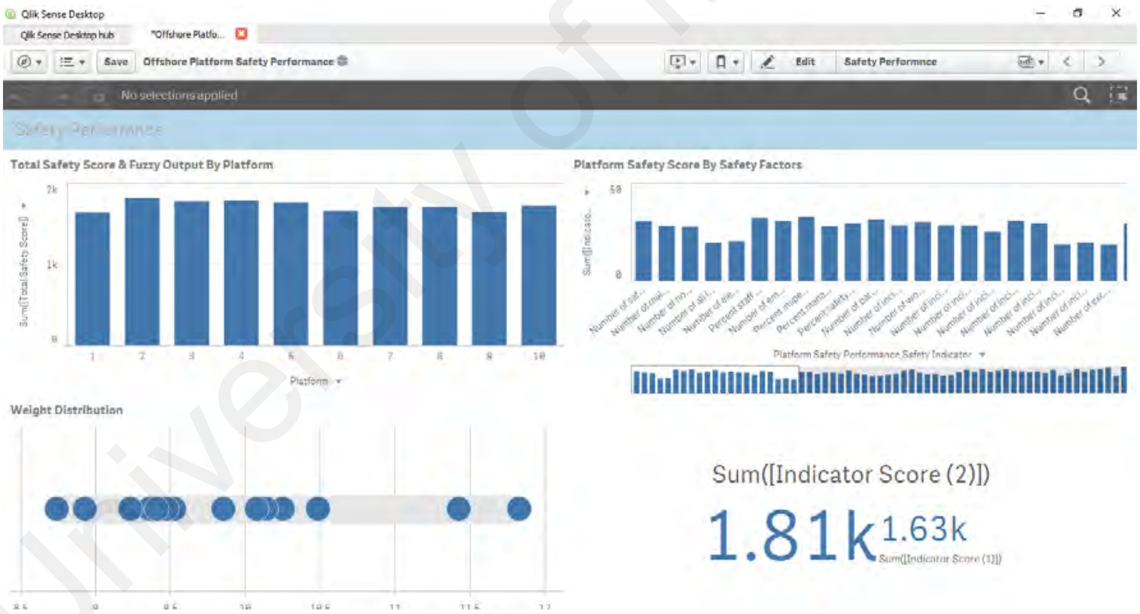


Figure 4.24: Dashboard Presentation of Safety Performance Data

CHAPTER 5: DISCUSSION

5.1 Overview

This chapter provides an account of the low ratings garnered for perceived risk of failing to observe the safety performance indicators in comparison to the perceived importance ratings before featuring the important correlations drawn from the correlation analyses of perceived importance and perceived risk ratings of the safety factors. It attempts to explain the similar correlation results obtained from different correlation analyses performed.

This chapter also discusses the sensitivity analysis performed and justifies the use of weights for scoring which are derived from multiplication of perceived importance and perceived risk ratings, based on sensitivity analysis. It continues on to explain the testing results of the fuzzy inference system, particularly on the variations of crisp outputs over a narrow range of total safety scores, as well as how the membership functions, defuzzification methods, rules, and architecture of the fuzzy inference system affect the crisp outputs.

In addition, this chapter discusses the correlations between safety factors obtained from testing of the safety performance measurement framework with actual safety performance data of 10 offshore oil platforms, and compared the correlations against those identified from perceived importance and risk ratings. It demonstrates how the safety factors are related to lagging performance such as incident rate and highlights the potential of the framework for prediction or quantification of incident rate. It accounts for validation of the framework against the facility status report used to gauge performance of hardware on platforms. This chapter ends with a summary of significance of the study's findings and its limitations which serve as the basis for future study.

5.2 Relevance of Safety Indicators and Framework

Øien et al. (2011) is of the opinion that operational experts should be involved in evaluation and selection of indicators to account for face validity. This study had demonstrated face validity via consultation with industrial practitioners in delineation of safety performance indicators and development of the framework, as well as execution of the questionnaire survey on perceived importance and perceived risk of the indicators among health and safety practitioners in major oil and gas companies in Malaysia.

The final 63 indicators were affirmed to be relevant to safety performance measurement of offshore oil and gas platforms via literature review, inputs of industrial practitioners and perceived importance ratings obtained from questionnaire survey. The industrial practitioners reflected that the indicators cover the major aspects of personal safety and process safety, encompassing elements related to organizational climate, competence, resilience engineering, safety critical elements as well as legal compliance. Resilience engineering was highlighted in change and emergency management. Indicators related to resilience engineering are regarded as resilience based early warning indicators (REWI) by the SINTEF.

The comprehensive indicators, hence safety performance measurement framework is in line with the promulgation of Ren et al. (2008) of a holistic systemic approach towards offshore system which includes all functional entities, with identification of their inter-relations to prevent accidents. The reason is that offshore installations are complex and accidents on the installations are multi-causal involving human factors in addition to defective equipment and operations.

The integrative framework also addresses the lack of focus on process safety and over-reliance on lagging indicators highlighted by the US Chemical Safety Hazard Investigation Board (2012) on offshore safety management post Macondo blowout. It resonates with the EU Commission's recommendation of pooling data for more complete offshore safety representation as well as the inclusion of near misses and standardization of data collection and presentation format (Christou & Konstantinidou, 2012).

A corporate sustainability report had promulgated inclusion of contractor and project health, safety and environment management, process safety and asset integrity, human factor, emergency response, as well as inculcating HSE capability and culture in safety performance monitoring, in addition to key safety indicators encompassing fatality accident rate, lost time injury frequency and loss of primary containment (Petronas, 2013). This is in line with the safety factors identified in this study, indicating that the safety factors generally agree with what are considered important by the Malaysian oil and gas sector in monitoring safety performance of offshore oil and gas platform's operations. These key areas can potentially be the basis of benchmarking safety performance of offshore oil and gas platforms nationwide.

5.3 Low Rating of Perceived Risk in Comparison to Perceived Importance

The multi-factorial causation of major incidents is well-illustrated by Reason's Swiss Cheese Model (1990). Integrity and strength of barriers in the Swiss Cheese Model can be monitored using both lagging and leading indicators with lagging indicators revealing weaknesses in the barriers and leading indicators monitoring strength of the barriers. However, perceived risk at a workplace and the barriers integrity indicated by the indicators are not well defined (Zohar, 2000).

In line of the Swiss Cheese Model, low perceived risk ratings in comparison to perceived importance ratings in this study can be attributed to multi-factorial causation of major incidents, which is also echoed by Sarshar et al. (2015) that major accidents particularly are caused by factors related to design, operation, maintenance, and organizational arrangement. This probably leads to reservation in attributing incidence occurrences to only one type of failure when rating perceived risk (Rundmo, 1992).

Extensive studies are available on how people perceive risk. Risk perception is subject to confirmation bias wherein people tend to perceive greater risk of an event which supports their view though evidence may show the contrary. Risk perception is also affected by availability heuristic in the sense that an event that can be recalled at ease or is similar to one they have experienced before is usually perceived to have higher risk (Slovic et al., 1980). Also, the low perceived risk rating can be influenced by conjunction fallacy which causes the perception of lower probability or risk if the outcome alone is considered instead of both outcome and likelihood (Slovic et al., 1980). In this study, the respondents were asked to rate their perceived risk due to failure to observe or implement a particular safety indicator without stressing on probability of the failure. This could result in consideration of only the outcome of failure alone.

As perceived risk is subjective and personal, incorrect estimation is likely especially in situations where information is inadequate and the ability of mastering the risk is overestimated. Rundmo (1994, 1995) reported job stress of workers on offshore petroleum installations as well as experience of injury, regardless of whether the workers actually experienced accidents, affect their risk perception. He also reported a lack of significant difference in perceived risk, safety status and job stress between high-risk and low-risk installations (based on number of accidents) among study respondents who experienced injury before.

The study of risk perception is conventionally linked to personal aspects of safety such as job stress and psychosocial risk. This study presents a preliminary endeavor to relate other aspects of safety, particularly process and asset integrity as well as a more diverse domain of personal safety including chemical and noise exposure, to perceived risk via a set of selected indicators

5.4 Correlations between Safety Factors

5.4.1 Perceived Importance Ratings

Operational Condition Safety (OTS) model derived from QRA in the offshore oil and gas sector identifies seven performance standards, i.e. work practice, competence, communication, management, procedures and documentation, workload and physical working environment and management of change (Sklet et al., 2010). This matches partially with group 2 of factor analysis (**Table 4.9**). Start-ups and shutdown operations form part of work practice while instrumentation and alarms can be perceived as means of communication, in relation to OTS. Nonetheless, a major dissimilarity between group 2 of factor analysis and the OTS model is that the former does not include management of change (**Table 4.9**). **Figure 4.5** shows that plant operations and operating procedures are linked to hazard identification and risk assessment. Good operating procedures often dictate the need of hazard identification and risk assessment, and facilitate such endeavors by demanding close monitoring of safety critical operations (Dejoy et al., 2004). In fact, an indicator under ‘plant operations and operating procedures’ which spells ‘number of process hazard analysis recommendations related to inadequate operating procedures’ indicates close relation between both the safety factors.

Emergency management is clustered with MWE on safety and inspection and maintenance in group 3 of factor analysis (**Table 4.9**). Group 3 comprises components of resilience engineering. Resilience engineering aims at maintaining or increasing the ability of a system to sustain operations after changes and encompasses organizational and human aspects such as preparedness, learning culture, awareness, buffering capacity, goal conflict, monitoring and responding (Sarshar et al, 2015). In general, the resilience attributes in the development of Resilience based Early Warning Indicators (REWI) comprise three contributing success factors i.e. risk awareness, response capacity and support (Størseth et al., 2009). Emergency management relates to response capacity in the sense that it ensures timely and effective response to incidents. MWE on safety contributes to risk understanding, hence risk awareness under the organizational and human attributes of resilience. Inspection and maintenance is multifaceted, covering both risk awareness and response capacity. Inspection provides a channel of bringing risk to attention while maintenance revolves around correcting operational deviations and ensuring structural and process integrity (Øien et al., 2012). While group 3 consists entirely of REWI, REWI are also found in other groups for instance change management as well as hazard identification and risk assessment in group 1, indicating that resilience is a core aspect of safety, as much as safety culture.

MWE on safety is an important measure of safety climate that affects multiple safety factors, including emergency management. Good safety climate has been linked to good emergency management (Vinnem, 2010). This is captured in **Figure 4.5**. In addition to safety climate manifested partly via MWE, design of emergency devices, competence of emergency teams, attitudes, and perception of level of protection are crucial to emergency management. Different views arise in the role of emergency preparedness versus preventive measures in managing safety. While preference is given to preventive measures, emergency preparedness should not be discounted (Vinnem, 2010).

There is increasing literature in establishing the effect of safety culture and safety climate on occupational safety incidents such as injuries and fatalities. Safety culture and climate relate to human and organizational factors and are often reflected by safety management, colleague involvement and collaboration (Rundmo and Hale, 2003; Guldenmund, 2007). Mearns et al. (2003) highlighted a positive correlation between safety climate performance and number of accidents. Shannon et al. (1997) demonstrated that management's attitude and concern contribute towards improved safety performance of offshore sector in the UK. It is logical that MWE on safety, being a measure of safety climate and management attitude, is associated with the majority of safety factors. This is echoed by a study of Morrow et al. (2014) which suggested correlation between safety climate and measures of safety performance in nuclear industry in the US.

In addition, Morrow et al. (2014) demonstrated a negative correlation between training quality and unplanned scrams in nuclear power operations, indicating that higher training quality leads to lower unplanned scrams. Effective training has been linked to acquisition of competence and skills in performing a particular task (Swart et al., 2012). This indirectly implies that training leads to competence which subsequently leads to less deferred start-up and unplanned shutdown. Therefore, respondents who perceived competence as important also tended to perceive start-up and shutdown as important (**Table 4.14**).

Personal safety attributes positively correlate with number of incidents & near misses (**Figure 4.5; Table 4.14**). Offshore shift arrangement, for instance, has been associated with increased operational risks as a result of fatigue and sleep disruption which in turn, may increase the risks of injury and illness (Parkes, 2013). Rosa (1995) identified noise, chemical exposure and workload as potential contributors to fatigue which could increase risks of accident, back injuries and safety compromises.

Though there are numerous studies investigating the critical safety factors affecting safety of the oil and gas sector in general or in relation to specific processes, few are dedicated to examine the correlations between the safety factors. Studies on the relation between safety factors have conventionally focused on the psychosocial and organizational aspects (Leveson, 2015; Swuste et al., 2016). This study presents a preliminary attempt to examine how a wider range of safety factors are connected with each other in the Malaysian offshore oil and gas sector.

5.4.2 Perceived Risk Ratings

Table 4.11 shows that only two overarching safety components were identified via factor analysis of the perceived risk ratings of the safety factors, in contrast to the perceived importance ratings (**Table 4.9**). Nonetheless, some similarities of the components' elements with those for perceived importance ratings can be observed. For instance, contractor safety, management of plant change, plant operations and operating procedures, plant design as well as hazard identification and risk assessment are categorized under one component in both factor analyses (**Table 4.12**). This further confirms the inter-relation between plant operations and operating procedures, and hazard identification and risk assessment mentioned in the previous section.

Besides, inspection and maintenance, MWE on safety and emergency management are also grouped together in the factor analyses for both perceived importance and perceived risk, confirming the inter-relations of indicators monitoring resilience attributes, i.e. the REWI as proposed in **Section 5.4.1**.

A meta-analysis by Christian et al. (2009) showed that number of accidents and injuries are significantly associated with group safety climate, in line with the results of factor analyses in this study which invariably group number of incidents and near misses with organizational climate factors such as MWE on safety. Personal safety also contributes to number of incidents in a workplace and is invariably grouped with number of incidents and near misses in both factor analysis and hierarchical analysis of perceived risk ratings (refer **Table 4.12** and **Figure 4.7**). The correlation has been accounted for in **Section 5.4.1**.

The dendrogram (**Figure 4.7**) also shows close association between MWE on safety and emergency management, parallel to the findings of Vinnem (2010) as mentioned in the previous section. **Figure 4.7** demonstrates close relation between plant design and instrumentation and alarm. Risk control in plant can generally be grouped as emergency shutdown system, engineering control, isolation, dilution and dispersion as well as alarm and fault detection (Chia et al., 2003). Risk control plays the important role of thwarting accident propagation should operating conditions get out of control. Rathnayaka et al. (2014) proposed a risk-based inherent safety index which incorporates risk reduction in design options in addition to control of operating conditions where risk control index is inversely related to the inherently safety risk. A lower inherent safety risk represents a better process or plant design option. The risk-based inherent safety index suggests a relationship between plant design and instrumentation and alarm whereby design options with higher risk control consisting of better instrumentation and alarm are preferred. Apart from the inherent safety approach, a well-designed plant is often one with sufficient and responsive instrumentation and alarm system, which justifies the correlation between plant design and instrumentation and alarm.

Correlations between safety factors based on perceived risk of incidence occurrence due to failure of the respective factor is an area which is understudied. As mentioned, studies related to correlations between perceived risks of safety factors are often oriented to personal safety (Rundmo, 1992; Rundmo, 1995). In addition, perceived risk in those studies was treated as a single attribute rather than separate variables in relation to safety factors as in this study. The reason is largely due to the multi-causal nature of accidents. Attaching perceived risk to the absence of a particular safety indicator can be a difficult judgement.

On a general note, where personal safety is concerned, Mearns et al. (2010) reported that unsafe behavior is significantly related to, hence the best 'predictor' of number of self-reported accidents and near misses. A study involving underground mines workers shows that work injuries, negative affectivity and job dissatisfaction cause workers to take more risks and behave unsafely (Paul & Maiti, 2007). While the correlation between personal safety and number of incidents and near-misses are shown in this study, the aspects of personal safety which contribute to incidents and near-misses are not pinpointed.

5.4.3 Perceived Importance of Safety Factors and Perceived Risk of Failing to Observe the Safety Factors

While there is no comparable study in relating perceived importance of safety indicators against perceived risk of incident occurrence due to failure to observe the corresponding indicators, studies on safety climate have pointed to a direct correlation between factors consisting of environmental conditions, safety policies and programs, organizational climate as well as safety climate, and perceived safety at work (Dejoy et al., 2004). Hofmann & Morgesan (1999) highlighted that the correlation between organizational support and workplace accidents are mediated by safety-related communication and safety commitment. Earlier studies conducted had in fact indicated that perceived management support is related to workplace safety conditions (Witt et al., 1994; Thompson et al., 1998). It has been suggested that more studies are needed to establish a more definitive relationship between safety climate factors and perceived safety at work, which also relates to how likely workplace incidents are perceived to occur (Thompson et al., 1998; Dejoy et al., 2004).

A recent study by Kouabenan et al. (2015) showed that safety climate has a mediating effect on perceived risk associated with management involvement in safety management. A positive correlation was observed between perceived risk and management involvement in safety management as well as between perceived safety climate and such involvement. The study revealed that level of management involvement increases with level of risk perceived. This indicates correlation between perceived risk and perceived importance in management involvement in safety management though confirmatory study is required.

Generally, studies have pointed to the correlation between perceived risk and protective behaviors (Arezes and Miguel, 2008; Gandit et al., 2009) and these studies were mostly personal-safety oriented. In most studies concerning perceived risk, the risk is treated as a variable affected by the overall performance of safety factors. This study, however, associates risk with failure of a particular safety factor, thus, giving rise to multiple risk variables. A search through journal databases reveals a lack of research investigating correlations of safety factors other than organizational and human, and correlational studies are dominated primarily by those related to safety climate, safety culture and organizational culture. This study presents a potentially new dimension of looking at how different process and personal safety factors affect risk perception and shows a weak correlation between perceived importance ratings of safety indicators and perceived risk ratings due to failure to observe the indicators. The weak correlation is indicated by the low Pearson coefficient (**Table 4.13**) as well as a plot of mean perceived risk against mean perceived importance ratings of the safety factors (**Figure 4.2**) and safety indicators (**Figure 4.3**) respectively.

5.4.4 Pearson Correlation of Perceived Importance Ratings

Pearson Correlation was conducted for comparison with the correlations among the safety factors demonstrated by factor analysis (**Table 4.9**) and hierarchical clustering (**Figure 4.5**). The results show that Pearson's r (**Table 4.14**) are largely in line with the hierarchical clustering which also agrees significantly with factor analysis.

Hierarchical clustering and factor analysis aim to segment or reduce data by grouping them based on similarity. Fundamentally, hierarchical clustering segments variables into groups where variables within a group have larger similarities in comparison with variables between groups (Yim & Ramdeen, 2015). Principal component analysis employed in factor analysis, however, assigns data set with highest variance into a principle component, hence minimizing separation of data and enabling dimension reduction. In practice, when dealing with data sets of high dimensions, the principal components of principal component analysis often correspond to how the variables are separated in hierarchical clustering, thus supporting similar interpretations (Mulaik, 2010). Therefore, the variable clusters of dendrogram produced in hierarchical clustering are often in agreement with the variables grouped under the principal components in factor analysis (Soneson, 2016). Nonetheless, the principal component analysis provides a cleaner representation of the variables categorization though it does not detail how the variables are linked to each other.

Hierarchical clustering presents the correlation between variables based on Euclidean distance. While Euclidean distance score ranges from 0 to 1, Pearson's r ranges from -1 to +1. In both cases, 1 indicates perfect correlation between two variables. Berthold and Höppner (2016) reported that Euclidean Distance normalized with z-score behaves similarly to Pearson's r. Z-score, also known as standard score is dimensionless quantity calculated as below:

$$Z = \frac{x-\mu}{\sigma} \qquad \textbf{(5.1)}$$

where Z = z-score or standard score, χ = raw score, μ = mean of the population, and σ = standard deviation of the population

Generally, it is agreed that Euclidean distance and Pearson's r are appropriate for distance measures with Euclidean distance being more suitable for log ratio data and Pearson's r more suitable for absolute value data (Costa et al., 2014).

5.5 Establishment of Safety Performance Measurement Framework

5.5.1 Sensitivity Analysis

The sensitivity analysis employed in this study is a simplistic one-at-a-time analysis where the compliance status of a set of indicators with the highest and lowest weights were changed respectively at a time to examine how the total safety score was affected. Ideally, the total safety score should be sufficiently sensitive to the weights of the indicators and changes in the compliance states of the indicators.

There is a lack of consensus in what level of sensitivity index is considered acceptable as it frequently depends on the scenarios and applications of the sensitivity analysis. Nonetheless, the SI variations demonstrated by altering the parameters of interest are clearly observable for using weights derived from multiplication of perceived importance and perceived risk ratings, as well as from perceived risk ratings solely where the former exhibits greater sensitivity, hence selected for the framework.

5.5.2 Testing of Fuzzy Inference System

Swuste et al. (2016) highlighted a lack of empirical research on indicators identification which were conventionally conducted by individual companies, and the topic of process safety indicators is still under-discussed. Swuste et al. (2016) was of the opinion that major accident analysis and development of safety indicators are inseparable from studies related to decision making. The adoption of indicators is recommended for effective decision making in the presence of copious data which are otherwise meaningless. As such, a safety performance measurement framework using the list of indicators proposed is developed to highlight the status of safety factors, hence the overall safety of offshore oil and gas installations for better decision making. Fuzzy inference system is incorporated into the safety performance measurement framework due to its resemblance to human thinking via the use of linguistic terms, ease of use and ability to capture expert's opinions via the what-if rules (Gerla, 2001).

Table 4.18 shows a satisfactory agreement between the total safety scores (presented in **Table 4.16**) and the crisp outputs of the fuzzy inference system though the linguistic outputs of Platform 1 vary from 'slightly deviated' for Scenarios A and C to 'compliant' for Scenario B. More than one rules in both the scenarios were triggered by the marginal scores of management and work engagement and number of incidents, which fulfilled the 'deviated' membership function in both Scenarios A and C to a higher degree. Together with a fully 'deviated' state for start-ups and shutdown, there were three 'deviated' states, thus satisfying the rule for a 'slightly deviated' output. The crisp output of trapezoidal membership function (Scenario B) for Platform 1 is higher in relation to the other two scenarios as the trapezoidal membership function has a lower support limit for scores considered 'fully compliant'. The lower support limit of the membership function allows the marginal scores to be identified as 'compliant' (Shaout & Yousif, 2014). Nonetheless, the trapezoidal membership function did not seem to make a distinction between the safety scores of Platforms 2, 3, 4, 7, 8 and 10 as indicated in the same crisp outputs for the platforms (**Table 4.18**), though the Platform 2 has a higher total safety score.

Defuzzification using mean of maxima generally gave higher crisp outputs compared to center of area (**Table 4.18** and **Table 4.19**), consistent with few previous studies, for instance a study by Naaz et al. (2011) using fuzzy inference engine to generate status of load balance node with load and number of heavy load node as input and another by Azadeh et al. (2008) for health, safety, environmental and ergonomics performance assessment. Exceptions, nonetheless, were found in scenarios with 'non-compliant' status (**Table 4.19**).

For scenario testing (**Table 4.19**), irregularities were observed between the crisp output and the safety scores. For instance, membership function scenarios A and C gave a higher crisp output for Scenario 2 with lower safety score than Scenario 1 (**Table 4.19**). Similar trend was observed between Scenario 2 and Scenario 3, except with trapezoidal membership function and membership function scenario (C) with MoM defuzzification. This is further portrayed in **Figure 4.18(a)** and **Figure 4.18(b)** where one total safety score or two very close safety scores can yield two distinct crisp outputs. For scenarios with 'highly deviated' state, the crisp outputs of all membership functions remained fairly constant at or near 50 though safety scores varied. The crisp outputs, hence the linguistic outputs corresponded well with the rules defined by the industrial practitioners but not entirely with the safety scores (Bandemer & Gottwald, 1995).

It can generally be observed that crisp outputs correlated with rules entered into fuzzy inference system, since the rules fundamentally map the inputs to the outputs. Taking Scenario 11 for instance, though its safety score is higher than Scenario 9, the industrial practitioners were not comfortable to assign 'highly deviated' state to a system that has no compliant safety factors. This is a typical scenario of complex decision-making based on experience. Instead of solely depending on scores, decision making should also be based on industrial experience and knowledge which evolve over time (Chia et al., 2003). A system's state of compliance can also be determined by demarcation of the total safety score but a high score does not necessary reflect the collective well-being of the system. This is akin to a common academic scenario where passing a subject sometimes depends on the conditions set, for instance a necessity to pass the final exam, rather than the marks obtained from other assessment components (Elton & Johnston, 2002).

When the safety score was plotted against the crisp outputs, a linear plot was hardly observed. Nonetheless, the data were tested of how well they agreed with the fitted regression line which was indicated by R-squared value (Devore, 2011). The R-squared values of all membership functions and defuzzification tested did not vary significantly, with the value of Scenario C (triangular and trapezoidal membership function) being the highest [**Figures 4.18(a) and 4.18(b)**]. The R-squared values are generally on the high side, indicating that the crisp outputs generally increase as the safety scores increase, though not necessarily linearly. This is attributed to fuzzy rules of the fuzzy inference system which may represent non-linear mapping of fuzzy input data to an output value (Bai & Wang, 2006). The fuzzy rules defined by the industrial practitioners in this study, outweigh the safety scores in determining the levels of safety performance, hence the crisp outputs of the platforms. The crisp output is essentially an aggregation of the outputs of rules in the fuzzy inference system triggered. As more than one rules can be triggered, the crisp outputs are also affected by the number of rules triggered (Sinha & Gupta, 2000; Bai & Wang, 2006). Nonetheless, four clusters of crisp outputs can be observed in **Figures 4.18(a) and 4.18(b)**, corresponding to the four levels of safety performance defined, with 'non-compliant' at the bottom to 'compliant' at the top of the plot.

It is commonly agreed that trapezoidal membership function usually works well with the definition of any concept and triangular membership function is a special type of trapezoidal membership function (Zheng et al., 2012). Studies on the use of fuzzy inference system for performance evaluation commonly used triangular and trapezoidal membership functions (Kwong et al., 2002; Azadeh et al., 2008; Yang et al., 2011). A study by Kwong et al. (2002) attempted to integrate scoring system and fuzzy expert system for assessment of suppliers in manufacturing companies. Similar to this study, the fuzzy expert system integrates the supplier selection factors using a mixture of triangular and trapezoidal membership functions. However, the study did not test how different scenarios of membership function affect the outputs as well as the relation between the actual scores and the index generated from the crisp outputs.

On a different note, the three platforms tested were generally well-performing with Platform 2 having the highest total safety score. Platform 2 also had the lowest total recordable injury rate and near misses compared to the other platforms (**Table 4.21**). The actual number of near misses on Platform 1 was the highest (**Table 4.21**) thus corresponding to its marginal score for number of incidents which fell into the 'deviated' zone of the triangular membership function. Problems related to start-up and shutdown as indicated by marginal scores in more than half of the platforms (**Table 4.16**), according to the industrial practitioners consulted, is common due to factors such as availability of vessels, accommodation restrictions, shutdown scope growth, equipment availability and reliability, etc.

5.5.3 Testing of Alternative Set-up of Fuzzy Inference System

Rule setting for the fuzzy inference system was complicated by the number of safety factors involved. Though the safety factors represent fundamental entities of this safety performance evaluation framework, the factors can be combined to form intermediate fuzzy models which then feed into an integration model to simplify rule-setting. An attempt was made to integrate the safety factors into intermediate entities which feed into the integrated model. The set-up was based on the dendrogram of perceived importance ratings of the safety factors (**Figure 4.5**).

As the intermediate entities break up the variables into smaller groups, they enable less variables to be considered during rule-setting, thus simplifying the process. Similarly, the dendrogram for perceived risk of the safety factors (**Figure 4.7**) can be used as the basis of the set-up but perceived risk ratings are affected by a number of factors as detailed in **Section 5.3**, and are not as straight-forward as the perceived importance ratings.

The advantage of such architecture is that the intermediate entities can generate indices for a sub-group of variables regulating a particularly domain, for instance, health, safety or environment (Azadeh et al., 2008). A similar architecture was also promulgated by Kwong et al. (2001) for supplier assessment. The choice of fuzzy inference system architecture relies on its practical application and there is generally a lack of comparison between the performances of different architectures. The fuzzy inference system of Azadeh et al. (2007) used the performances of indicators as the input variables to respective intermediate entities consisting of health, safety environment and ergonomic assessments to measure the overall performance of a gas refinery. However, this approach may not suit well for this study due to the number of indicators and safety factors involved which may complicate rule-setting. Several literature related to fuzzy inference system have recommended approaches which simplify rather than complicate rule-setting, and stage-wise fuzzy reasoning by clustering critical factors which are related (Kwong et al., 2001; Azadeh et al., 2007; Shaout & Yousif, 2014).

Rules setting can be achieved by gathering experts' opinions or basing on actual data. The latter indirectly relies on expert knowledge because the selected variables and the number of data points are determined by experts. Rules based on data are usually applicable to controller type of fuzzy system (Gerla, 2001). This study presents a new framework of determining compliance states of offshore oil and gas platforms with no previous data serving as reference. It solely relies on the qualitative rules contributed by the industrial practitioners. The fuzzy system proposed is meant for performance measurement rather than controller. Testing of the alternative architecture with different degrees of overlapping for membership functions of intermediate output shows that highly overlapping membership functions produce a more consistent increase of crisp outputs with total safety score as depicted by the plot pattern and the highest R-squared value [**Figure 4.22(b)**]. Nonetheless, in all cases of membership functions and defuzzification tested, perfect linearity between the crisp outputs and total safety scores were hardly observed. This is in line with the findings of Wang (2015) that achieving acceptable linear performance for multiple input single output fuzzy inference system poses challenge as it involves complex set-up of output membership functions.

The ranges of value of membership functions for intermediate outputs dictating what is compliant, deviated and non-compliant also affect the final outputs. For instance, non-overlapping membership functions yielded higher final crisp outputs hence better linguistic outputs for Platforms 3 and 4 [**Table 4.20(a),** as compared to **Tables 4.20(b)** and **4.20(c)**] as the state of compliant is clearly defined by an output of 70 and above, unlike the slightly overlapping membership functions with compliant state only prevalent near 80 (**Figure 3.16**) and highly overlapping membership functions with compliant state predominant near 75 (**Figure 3.17**). As the intermediate outputs also serve as inputs of the final integration model, an intermediate score of 70 is translated as compliant for the non-overlapping membership functions scenario, and deviated for other cases. Upon matching with the rules set, the crisp and linguistic outputs generated may be different.

5.6 Validation of Safety Performance Measurement Framework

5.6.1 Comparison against Lagging Performance and Previous Correlations of Safety Factors

The safety performance evaluation framework presents an integrative approach in measuring the safety performance of offshore oil and gas platform based on 14 safety factors. The number of indicators under each safety factor varies, hence the maximum score for each safety factor. All the platforms had above average performance with Platform 2 topping the list, indicating that the platforms were generally well managed.

Table 4.17 shows higher variation, hence variance of number of incidents and near misses, as well as operation and operating procedures among the platforms. The former was attributed primarily to difference in number of incidents and near misses caused by contractors or visitors, during start-ups and shutdown, and where operational shortcuts were identified. The latter was due to missing indicators under the safety factor in few platforms. The compliance status for number of incidents and near misses was in agreement with the actual lagging performance of the platforms which was based on the fatality, injury and near misses. Higher total recordable incident rate and near misses of Platform 1 (**Table 4.21**) was confirmed by its lowest score for this safety factor among the platforms (**Table 4.16**). The same was observed for Platforms 6 and 9. This demonstrates that the score of number of incidents and near misses in the framework should inversely correlate with the actual number of injuries and near misses reported where a higher score indicates higher compliance. As the score of number of incidents and near misses was dependent on the actual number of injuries and near misses, a higher compliance score indicates lower number of injuries and near misses. The correlation is captured by Pearson correlation showing significant negative correlation between number of incidents and near misses, and total recordable incident rate as well as number of reported near misses (**Table 4.22**).

It has been demonstrated earlier that MWE on safety, number of incidents and near misses, contractors' safety, management of change, plant operations and operating procedures, plant design, personal safety as well as hazard identification and risk assessment were more connected than the other safety factors via perceived importance of the safety (**Figure 4.5**). Correlation analysis in **Table 4.22** shows that MWE was significantly positively correlated with personal safety, contractors' safety, management of change as well as plant operations and operating procedures, in line with **Figure 4.5**. Personal safety correlated significantly with MWE on safety, number of incidents and near misses as well as management of change, while contractors' safety correlated significantly with MWE on safety (**Table 4.22**), confirming the clustering in **Figure 4.5**. **Table 4.22** also reveals new correlations such as that between inspection and maintenance, and instrumentation and alarm, as well as between MWE and management of change which were not identified previously.

5.6.2 Potential for Development of Incident Frequency Prediction Model

Significant positive correlation between total recordable incident rate and near misses confirms the accident triangle where higher number of near misses leads to higher number of recordable incidents including injuries and fatality (Williamsen, 2003). Based on the accident triangle, near misses are always more than recordable injuries though different ratios between the two had been reported (Bellamy, 2015). The same is shown in **Table 4.21**. It is established that better safety climate leads to better safety performance, particularly accident and injury rates (Feng et al., 2014; Morrow et al., 2014). MWE, being a measure of safety climate, is shown to significantly and negatively correlate with total recordable incident rate (**Table 4.22**). Mearns et al. (2003) reported a significant association between management commitment and accident rate which supports the correlation between MWE and incident rate.

Both total recordable incident rate and near misses were inversely correlated to personal safety score. Personal safety encompasses noise exposure, cases of occupational diseases and occupational poisoning, fatigue, overtime, extended shifts and chemical exposure. Fatigue, overtime and extended shifts are aspects of psychosocial risks. Fatigue was linked to extended work hours, night shifts and rotating shifts (IPIECA-OGP, 2012), and was shown to negatively impact human performance leading to higher risks, hence injuries and near misses. Parkes (2010) reported that increased injury rates of offshore day work were related to circadian disruption as a result of night work and 'rollover' shift patterns involving shift change usually from nights to days in the middle of an offshore tour. Such shift pattern adversely affected sleep, performance and alertness. Nonetheless, Parkes (2010) also highlighted that shift extension from 8 hours to 12 hours did not cause significant negative impact on performance or health, in an onshore setting. Total recordable incidents also include occupational illnesses and poisoning which are elements of personal safety (IOGP, 2016). This study does not look into cases of occupational illness and poisoning specifically. Reiner et al. (2016) reported increased risk of machinery-related injury among male workers, workers of greater age as well as workers with history of injury and increased work hours in the US agricultural sector, which supports the findings that work arrangement and medical well-being of employees potentially affect the occurrence of injury.

This study reveals that lost-time injury rate was negatively correlated with the scores of operation and operating procedures, hazard identification and risk assessment, as well as instrumentation and alarm. While lost-time injury is a subset of total recordable incidents, correlation between these two entities in this study is not sufficiently significant. McVittie et al. (2009) reported that density of trained supervisor in the Canadian construction sector was negatively correlated with lost-time injury rate. The inverse relation between injury rates and level of experience was also highlighted in a study among seafarers and rig workers in the Western Australia offshore oil and gas industry (Martinovich, 2013). As experience relates to competence (Christian et al., 2009), this also supports a relatively high correlation ($r = -0.501$) between lost-time injury rate and competence. Though no established correlation was reported between lost-time injury and operating procedures, hazard identification and risk assessment has been identified as a crucial element of occupational injury and illness prevention program (Liu et al., 2010).

Regression models for prediction of incident rates including lost time injuries can be developed as more safety performance data of offshore oil and gas platforms is made available and presented via the framework. Attwood (2006) developed a quantitative model to predict accident frequency using combination of direct, corporate and external factors. A preliminary regression model based on testing of the framework on 10 offshore platforms is shown in **Table 5.1**, highlighting the safety factors that significantly influence the total recordable incident rate via stepwise regression method. Reliability of the model increases with increasing data and knowledge of offshore safety performance.

Table 5.1: Preliminary Regression Model for Prediction of Total Recordable Incident Rate

Safety Factor	Unstandardized Coefficients		Standardized Coefficients
	B	Std. Error	Beta
(Constant)	8.694	1.036	
Personal safety	-0.016	0.006	-0.525
Management of change	-0.023	0.009	-0.486

5.6.3 Comparison against Facility Status Report

Results of the framework were also compared against results of facility status reporting (**Table 4.24**) which is currently practiced on the platforms of an established oil and gas company. A major difference between the framework and the facility status report is that the latter is oriented towards hard barriers on the platforms comprising structures, equipment, vessel, physical system, etc. (**Table 4.25**). Soft barriers, i.e. competency deviation and standards are also included in facility status report but to a lesser extent than the framework proposed. Significant agreement is shown between results of the framework and facility status report. Platform 2 had the highest safety score which was also reflected by the compliance of all the SCE groups except process containment (**Table 4.24**). Deviation in process containment was in fact captured by the framework via the indicator of 'number of all hydrocarbon leaks' under the safety factor 'inspection and maintenance' which had a 'deviated' status.

Similarly, for Platform 3, deviation of process containment in the facility status report is associated with deviated state for 'number of all hydrocarbon leaks'. In addition, Platform 3 also registered a deviated state for shutdown system and emergency response in the facility status report due to isolated failure of certain hardware related to the two systems. The findings correspond to deviation in the 'number of elements of emergency procedure that fail to function to performance standard' under the safety factor of emergency management, as well as deviation in the ‘number of deferred start-ups & unplanned shutdown’ under the safety factor of start-ups and shutdown, in the framework. Isolated failures in the hardware might have contributed to increased failure of emergency procedure to meet performance standard as well as higher deferred start-ups and unplanned shutdown.

Sub-standard performance of number of all hydrocarbon leaks was a common problem in most of the platform studied. Hydrocarbon leaks is a major risk to accidents on offshore platform, hence a crucial safety performance indicator (Olsen, 2015). Based on a review by Sklet (2006), hydrocarbon leaks were mainly caused by operational error during routine production, maintenance-related latent failure, dissembling of hydrocarbon system for maintenance, technical/ physical failures, process upsets, and design related failures. These factors were largely captured by the safety factors used in the framework for instance inspection and maintenance, operation and operating procedures as well as plant design. Safety factor on ‘number of incidents and near misses’ has also associated operational shortcuts as a cause of incidents/ near misses reported. Besides causing other incidents/ near misses, operational shortcuts could potentially contribute to faulty process containment, hence hydrocarbon leaks (also see **Table 5.2**).

The effect of process upsets and hydrocarbon system integrity on hydrocarbon leaks was also demonstrated by the facility status report (**Table 4.24**) showing isolated failure of process containment. Nonetheless, the facility status report, as mentioned, is hardware-oriented and the performance standards set are in relation to the functional criteria of the hardware, such as fire water pumps under the protection system (**Table 4.25**). The framework proposed, however, links various crucial aspects of safety in determining the overall safety performance of a platform. It has also demonstrated the potential to relate the hardware shortfalls in the facility status reports to other leading deficiencies of the system. **Table 5.2** shows a comparison of the deviated items revealed by both tools and the potential cause-effect relationship. Operational shortcuts arisen due to unsafe acts at personal level or procedural shortcuts at facility level are identified as common causes of accidents in both construction and the process sectors (Kannan et al., 2016; Williams et al., 2017).

Table 5.2: Comparison of Deviated Items and the Potential Causation

Platform	Items with Deviated Status		Potential Cause-effect Relationship
	Facility Status Report	Proposed Framework	
2	• Process containment	• Number of all (hydrocarbon) leaks • Number of incidents/ near misses where operational shortcuts were identified	Operational Shortcuts → Faulty process containment → Hydrocarbon leaks
3	• Process containment • Shutdown systems • Emergency response	• Number of all (hydrocarbon) leaks • Number of elements of emergency procedure that fail to function to performance standard • Number of incidents/ near misses caused by contractors or visitors • Number of incidents/ near misses where operational shortcuts were identified • Exceedance of noise level • Number of deferred start-up & shutdowns	Operational Shortcuts → Sub-standard elements of emergency procedure → Faulty emergency response Faulty shutdown systems → Deferred start-up & shutdown

5.6.4 Correlation versus Causation

This study demonstrates correlation between the safety factors, as well as between safety factors and actual lagging performance. While it is arguable that correlation does not necessary relate to the causes of failure or incidents, it points to important interactions between safety factors which permit causation to be further investigated (Berthold & Höppner, 2016). The above shows that the framework facilitates identification of causation due to the use of indicators under 'number of incidents and near misses' which categorize incidents and near misses based on the causes. For instance, operational shortcuts captured by an indicator under the safety factor 'Number of Incidents and Near Misses' had been identified as a major contributor of total recordable incident rate (**Table 4.22** and **Table 5.2**).

Table 4.22 also shows that personal safety contributes to incident rate, which was generally agreed by the industrial practitioners as well as previous studies, such as that by Parkes (2010) indicating the link between shift arrangement, fatigue and increased risks of injury. The important correlation can be further probed by controlled investigation of worker groups subject to different shift arrangements, and results of accident investigations.

In offshore safety performance measurement and accident prevention, correlation and causation can work hand-in-hand. The EU Commission identified failure to identify and address risks as a common failure based on accident investigation (Christou & Konstantinidou, 2012). Correlation can then be used to devise strategies for more effective risk identification and control for instance by examining the operation and operating procedures as suggested in this study (**Table 4.22**). This matches with the lesson learnt from past accidents comprising hazard identifications during procedural changes and throughout the life cycle of oil and gas exploration (Christou & Konstantinidou, 2012). The framework therefore also facilitates lessons learning within and across facilities.

5.7 Significance of Findings

This study contributes significantly to performance measurement of offshore oil and gas platforms using an integrative framework. A literature search revealed a lack such framework and pointed to fragmented endeavors in this area for instance measurement of safety climate (Cox & Cheyne, 2000; Gadd & Collins, 2002; Transportation Research Board US, 2016), psychosocial risk (Bergh et al., 2014), organizational factors (Mearns, 2010; Skogdalen, 2011), fire safety (Beard & Santos-Reyes, 2003) and inherent safety at process design stage (Khan & Amyotte, 2004). The current performance reporting of offshore platforms focuses only on few lagging parameters particularly fatality and injury rates.

In addition, there is a lack of attempt to generate safety index using the fuzzy inference system. The findings of this study have pointed to the correlations between perceived importance of safety factors, as well as between perceived risk of failing to observe the indicators, which serve as the basis for score calculation and inputs of fuzzy inference system, for safety performance measurement of offshore oil and gas platforms. Correlations between perceived importance of the safety factors provide reference for architecture of the fuzzy inference system and rules setting.

The findings provide useful information in the architecture as well as selection of membership functions and defuzzification methods for deployment of fuzzy inference system in yielding safety index for offshore oil and gas platforms. While index generation using fuzzy logic has been attempted for other sectors for instance supplier assessment (Kwong et al., 2002), employee performance appraisal (Shaout & Yousif, 2014), as well as health, safety, environment and ergonomic system of gas refinery (Azadeh et al., 2008), the studies invariably lacked justification of the selection and testing of membership functions and defuzzification methods.

The framework validation findings show consistency with the current safety performance measurement of offshore platforms using lagging indicators i.e. total recordable incident rate, fatality, lost time injury and near misses, in addition to facility status report focusing primarily on physical barriers. This highlights the applicability of the framework to provide an integrative safety performance overview. The validation also proves certain correlations between safety factors identified based on initial perceived importance, which is instrumental to more effective and efficient safety management.

The framework also shows potential for amalgamation with dashboard technology in monitoring platform's safety performance and comparing performance between platforms. A comparison of the framework and the existing safety performance measurement on offshore oil and gas platforms in Malaysia are shown in **Table 5.3**.

Table 5.3: Comparison of the Proposed and the Existing Safety Performance Measurement Framework

Framework Proposed	Existing Practice	Significance
Integrative, combining crucial safety factors and indicators in the domains of process and personal safety.	Fragmented, with personal and process safety separated and emphasis placed on only few lagging indicators.	Integrative framework facilitates a more holistic and efficient safety performance measurement (Jacob, 2004).
Composite index/ score combining crucial domains of safety on offshore installations.	Non-composite, with accident, injury and fatality rates as well as loss of primary containment with major consequences highlighted. No index is provided.	Index permits tracking and comparison of safety performance (Khan, 2004). Composite index/ score facilitates monitoring of multiple crucial dimensions of safety (Hassan & Khan, 2012).
Crucial aspects of industrial hygiene have been included.	Industrial hygiene is a sub-domain of personal safety but have been undermined in the reporting of personal safety incidents.	Industrial hygiene monitors chemical and noise exposure of workers, which are often precursors of occupational illnesses (Abdullah & Basirun, 2013).
Emergency response which focuses not only on the hardware but the actions taken and frequency of training.	Emergency response under process safety often focuses only on the hardware such as fire alarms.	Emergency response also encompasses emergency preparedness of employees during emergency situations (Frens & Berg, 2014).
Leading indicators which measure the input to the safety system are used on top of lagging indicators.	Lagging indicators still assume a primary role in safety performance measurement and reporting.	The importance of leading indicators in safety management has been recognized (Reiman & Pietikainen, 2012).
Weights of indicators are derived from questionnaire survey leveraging on a larger population of experts.	Indicators are frequently treated as having equal weights. Where weights are assigned, it is often done by the management.	In reality, indicators are often not perceived to be equally important (Swuste et al., 2016).
Integration of fuzzy inference system to determine the compliance status of a platform.	As with monitoring, compliance reporting is often fragmented. The practice varies among oil	Fuzzy inference system facilitates interpretation of states of compliance and generates a crisp output

Framework Proposed	Existing Practice	Significance
	and gas companies with more advanced companies having process-oriented status reporting for platforms while others do not.	based on inputs of safety scores, which can potentially be used as safety index (Kwong, 2002; Zadeh, 2008).
Capture of expert's judgement and opinions in generating an overall safety index and compliance state for a platform.	Compliance reporting is itemized, based on hardware system, e.g. structural integrity and process containment. Attempt has yet been made to confer an overall compliance state to a platform. No integration of fuzzy inference system.	Variability of expert's judgement can be reduced in determining compliance state. Coding of priori knowledge in the system can be done, thus allowing decision-making in the absence of expert (Sa'idi et al., 2014). Nonetheless, human judgement is complex (Klir & Yuan, 1995) and a case-by-case consideration may be required.
Correlations between safety factors are presented for better understanding of synergies in safety management, hence improved efficiency.	Attempt has yet been made to present how one safety factor is correlated with the others.	Correlation study not only provides understanding of synergies between safety factors, it also provides basis for design of intermediate models of fuzzy inference system in order to simplify rule-setting (Ma et al., 2011).
Use of numbers, modified from the conventional traffic light system for indication of compliance states of safety indicators. The numbers can be combined with traffic light system.	Use of traffic light system to indicate compliance states of safety indicators.	Number permits calculation of safety scores. Scores of safety factors also serve as inputs of the fuzzy inference system.

5.8 Limitations

This study may seem to have underplayed the broader organizational factors, for instance management commitment to safety, decision-making, willingness to raise concerns, safety communication and training quality (Morrow et al., 2014) but it is justifiable as the study focuses on facility-level safety which encompasses the process and personal domains. While organizational factors have been identified as a major cause and predictor of accidents and near misses, they are not adequately established due to the breadth of the subject (Mearns, 2010). In addition, these factors have been subject to extensive studies (Haber et al., 1991; Hofmann & Morgeson, 1999; Øien, 2001; Mearns et al., 2010), thus prompting the study to delve into more specific organizational issues at facility level for instance, the MWE on safety, operation and operating procedures as well as competence.

Øien and Sklet (1999) highlighted that correlation between indicators and safety/ risk level is unclear and needs to be further investigated. It has been conventionally assumed that there is a positive correlation between indicators and safety, however, more studies are needed to confirm the influence of indicators on safety/ risk level of a facility. Øien and Sklet (1999) further commented that correlations between indicators, implementation of safety measures and plant safety is not adequately evaluated, prompting further confirmatory work. This study includes a preliminary initiative to identify the correlation between safety performance measurement of offshore oil and gas installations using the indicators proposed and the actual lagging safety performance of the installations particularly total recordable injury, fatality and near-misses. Nonetheless, a more extensive study is needed to confirm the correlation between perceived importance of the indicators and safety/ risk level. For instance, **Table 4.13** shows that perceived importance of management of plant change is positively linked to the perceived risk of failing to observe instrumentation and alarms safety. Subsequent study can use this premise as a hypothesis and examine the validity of the hypothesis.

Safety performance measurement using key indicators is a dynamic system subject to continuous improvement. It is crucial to review the relevance of the indicators periodically as the issues or areas of interest and their importance may change over time, thus, prompting the modification and removal of existing indicators and inclusion of new indicators. The indicators identified in this study can become irrelevant as time passes and new knowledge and technology are introduced (Hassan & Khan, 2012). Therefore, continuous improvement via periodic review of the indicators' relevance and update of the indicators is advocated.

Apparent limitation of safety performance measurement based on composite indicator is that it can be misleading if misinterpreted or not sufficiently constructed. Compliance status of the indicators are interpreted and aggregated via fuzzy inference system yielding an overall score. Over-reliance on the composite score without looking at how each safety factor performs can be detrimental as high-performing safety factors can mask low-performing safety factors, yielding high composite score despite apparent failure of certain safety factors. Also, difficulty in measuring certain performance areas may result in poor decision making due to failure to highlight areas of concerns requiring remedial action (Jacob et al., 2004).

Though deemed sufficient, statistical power of this study can still be improved via the number of responses generated both for the perceived importance and perceived risk ratings of the safety indicators in the first phase and the safety performance measurement of offshore oil and gas platforms in the third validation phase (Bradburn, 2004). The study depended greatly on the quality of responses provided by the respondents, the number of respondents participated as well as the professional experience and expertise of the respondents. While the received responses had been screened, it was difficult to control how the responses were provided during the course of the survey. The study targeted primarily at health and safety professional in the oil and gas industry. Statistically, a larger sample size will provide more significant results.

Fuzzy inference system of this study has some inherent limitations. Fuzzy inference system relies heavily on experts' knowledge and judgement, particularly in the determination of limits of membership functions and the rules for the output (Ren et al., 2009). Expert involvement was crucial in the study and posed the greatest challenge. As involvement of health and safety practitioners in the oil and gas sector was entirely on a voluntary basis, it was challenging to garner full participation in the study due to time constraint and work commitment. Acquiring safety performance data of offshore platforms also posed a major challenge due to confidentiality of the data and time required to extract the data and translate them into the format of the indicators used.

The rule-setting adopts a simplistic qualitative means of gathering rules contributed by the industrial practitioners. The number of variables involved eventually complicates rule-setting. A stage-wise fuzzy reasoning by introducing intermediate entities seems to simplify rule-setting while enabling the relative importance of safety factors to be considered. However, as knowledge in determining compliance states of platforms based on the safety factors are currently lacking, only limited rules are entered. As knowledge in this area grows, the rule base will grow and more reliable crisp outputs will potentially be generated for use as safety index (Fetscherin & Stephano, 2016).

The study is limited in the number of platforms which were tested using the safety framework. The reason is that the evaluation process was elaborate where the study participants needed to gather the information related to compliance of the indicators from multiple sources. Integrating the information into a single framework presented a tremendous challenge because safety performance monitoring in the offshore sector was fragmented into personal and process while the use of leading indicators monitoring documentation, organizational factors and competence especially, is limited. Facility status reports of platforms are not readily accessible and securing a full report even from one single platform presented great challenges due to corporate considerations and legal process.

CHAPTER 6: CONCLUSION AND RECOMMENDATION

6.1 Conclusions

In view of the recurrence and severity of accidents involving offshore oil and gas platforms, an effective safety performance measurement framework for the platforms is crucial. The framework should provide a well-rounded reliable indication of how the major areas of safety, i.e. process and personal safety, are performing and make use of leading indicators to gauge efforts and inputs channeled into the safety system, in addition to the commonly used lagging indicators. This study, therefore, proposes an integrative safety performance measurement framework for offshore oil and gas platforms in Malaysia, combining a scoring system based on 14 safety factors and 63 safety indicators against which safety performance of platforms are evaluated, as well as a fuzzy inference system to generate a composite safety index for the platforms based on experts' rules.

The study reveals important correlations between the safety factors via factor analysis, hierarchical clustering and Pearson correlation. It shows that membership function scenario combining both triangular and trapezoidal functions, with center of area defuzzification and overlapping output membership functions is most appropriate for overall safety status, hence safety index generation using the fuzzy inference system. For alternative architecture of the fuzzy inference system with grouping of input variables based on hierarchical clustering of perceived importance ratings of the safety factors, highly overlapping membership functions of the intermediate outputs generate crisp outputs which increased more consistently with total safety scores. Also, rule-setting is comparative simpler for the alternative architecture with stage-wise fuzzy reasoning as fewer variables were considered at a time.

Validation of the framework against the findings of facility status reports of two oil platforms demonstrates good agreement, for instance a deviated state for process containment in the facility status reports corresponded to partial compliance of the indicator ‘number of all hydrocarbon leaks’ under the safety factor ‘inspection and maintenance’ in the framework.

6.2 Significance and Implications of Findings

Accidents involving offshore platforms, either personal or process-related, have turned attention to the necessity of an integrative and effective safety management system, including performance measurement which pools important safety data from fragmented sources to provide a reliable picture of safety on the platforms.

This study captures the indicators most pertinent to safety performance measurement of offshore oil and gas installations in Malaysia. It contributes to streamlining information needed for safety performance measurement by presenting crucial process and personal safety data in an integrative framework, with inclusion of leading indicators monitoring safety inputs, as well as near-misses in accident reporting. The framework combines a scoring system which generates scores of safety factors based on the compliance statuses of the underlying safety indicators, and a fuzzy inference system which yields the overall compliance status and safety index of a platform based on experts’ opinions and experiences.

The framework reveals the potential of safety reporting based on the 14 safety factors identified in addition to the current use of lagging indicators comprising fatality and injury rates as well as hydrocarbon leaks. This facilitates safety performance comparison of offshore oil and gas platforms based on the key safety factors while providing flexibility in terms of data confidentiality. The scores of the safety factors can be presented without revealing the failures of the underlying indicators. The framework also opens up new dimensions for performance benchmarking in addition to the conventionally used fatality and injury rates. Effective benchmarking permits sharing of best practices and facilitates continuous improvement (Whewell, 2012).

The use of fuzzy inference system enables experts' opinions in relation to the compliance status of a platform to be captured. It also has the ability to generate a safety index for an offshore platform based on the rules set while providing a channel which enables the compliance statuses of the safety factors to be tracked. It can produce a linguistic output which dictates the overall compliance status of a platform. Overall, the framework portrays flexibility in accommodating new knowledge in offshore safety for decision-making, the emergence of new indicators and changes in performance standards or targets.

In addition, the framework enables correlations between the safety factors to be captured. This improves understanding on how the factors influence actual lagging performance of the platforms. It contributes to more effective accident prevention and more efficient safety management via synergy of the safety factors.

Application of the framework can be extended beyond the Malaysian context as there is a lack of attempt to generate composite safety indices for oil and gas platforms globally and corporate safety reporting of oil and gas companies outside Malaysia is also largely confined to the common lagging indicators such as fatality and injury. Nonetheless, the Malaysia-specific aspects of this study particularly the selection and weights of indicators should be improvised to fit the global context. The framework also demonstrates potential to be used in the industry through validation during which actual data of oil platforms were collected based on the framework. In addition, numerous indicators were sourced from industrial guidelines. A stage-by-stage adoption of the framework is a more realistic path allowing the oil and gas companies to gradually expand their reporting regime and adapt to the data format required by the framework.

6.3 Recommendations for Further Study

The list of indicators can be further screened or refined to ensure all crucial safety aspects of offshore oil and gas installations are included while redundant indicators are removed. Further study on 'non-technical' risk indicators has been suggested for monitoring of risks related to organizational and human factors. As such, indicators measuring organizational and human factors can be expanded, but not at the expense of other key safety aspects such as inspection and maintenance, personal safety, instrumentation and alarm, etc.

Where correlation studies are concerned, further studies can look into how process safety and asset integrity affect perceived risk in addition to personal and organizational factors which have been subject to much study. While the correlation between personal safety and number of incidents and near-misses is shown in this study, future studies can look into the particular aspects of personal safety that contribute to incidents and near-misses in order that a better accident prevention strategy can be devised, for instance how noise exposure contributes to incidents and near-misses.

Another potential area of further study can endeavor to refine the fuzzy inference system in terms of the indicators, rules, architecture of the system and the membership functions adopted. Improvement of the fuzzy inference system can be examined, particularly in relation to how the crisp outputs can be used as safety index of an offshore oil and gas platform. The fuzzy inference system can also be extended to evaluation of environmental, ergonomic and sustainability performance of the offshore platforms. Potential integration of artificial neural network with fuzzy logic in safety performance evaluation of the offshore platforms can also be probed.

Finally, more data of offshore platforms can be used for validation of safety performance measurement framework to establish a more reliable actual correlations between the safety factors used in this study and the actual lagging performance of the platforms, such as fatality rate, injury rates and near-misses. This enables influences of various safety factors on the lagging performance of the platforms to be highlighted, thus, permitting safety factors with high influence to be focused in safety management.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

Conference Papers

Tang, D. K. H., Md. Dawal, S. Z., & Olugu, E. U. (2015, September). *Factors affecting safety of processes in the Malaysian oil and gas industry*. Paper presented at the 4th International Conference on Advanced Manufacturing Technology, Skudai, Johor, Malaysia.

Tang, D. K. H., Md. Dawal, S. Z., & Olugu, E. U. (2015, December). *Factors affecting safety of processes in the Malaysian oil and gas industry*. Paper presented at the 10th CUTSE International Conference, Miri, Sarawak, Malaysia.

Tang, D. K. H., Md. Dawal, S. Z., & Olugu, E. U. (2017, November). *Integrating fuzzy expert system and scoring system for safety performance evaluation of offshore oil and gas platforms in Malaysia*. Paper presented at the Borneo Research Education Conference (BREC 2017), Miri, Sarawak, Malaysia.

Tang, D. K. H., Md. Dawal, S. Z., & Olugu, E. U. (2017, December). *Actual safety performance of the Malaysian offshore oil platforms: Correlations between the leading and lagging indicators*. Paper presented at the One Curtin International Postgraduate Conference (OCPC 2017), Miri, Sarawak, Malaysia.

Journal Articles

Tang, D. K. H., Md. Dawal, S. Z., & Olugu, E. U. (2017). Factors affecting safety of processes in the Malaysian oil and gas industry. *Safety Science*, *92*(2017), 44-52. Published (ISI-indexed journal).

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