Faculty of Health Sciences
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The Relationship Between Human Factors and Plant Maintenance Reliability in a Petroleum Processing Organisation

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Signature: ………………………………………….

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Abstract

Despite the considerable emphasis on improving maintenance reliability in the petroleum industry by adopting an engineering approach (International Standards Organization, 2006b), production losses, ineffective maintenance, and major disasters continue to occur (Urbina, 2010; Pidgeon, 2000). Analyses of these events have indicated that a failure to consider the human factors in the design (Taylor, 2007), operation (Øien, 2001a), or maintenance (Bea, 1998) of hazardous process technologies is often an important contributor. Based on research to evaluate the influence of these human factors on organisational performance, various models (Rasmussen, 1982; Dekker 2005) and taxonomies (Reason, 1998) for analysing organisational processes at the individual-, group- and organisational-level have been developed.

By using these models, the current research was designed to determine the influence of human factors on maintenance reliability in petroleum operations. Three studies were conducted in petroleum operations with the objective in the first two studies of identifying the most-frequent contributors to maintenance-related failures, and in the third study, determining if group differences between higher and lower reliability work areas could be differentiated on the basis of these human factors.

In Study 1, the *First Priority* incident database of the target organisation was used to determine the most frequently reported human factors in maintenance-related, lost-production failures. The most-frequent factors in the incidents (N=194) were found to be *Violations*, *Design & Maintenance, Detection,* and *Decision-making.* These results accorded with earlier studies in the field of human factors (Hobbs & Williamson, 2003; Lawton 1998), which frequently identified human error and violations as the causes of failures. Study 2 provided a more rigorous investigation of the organisational contributors to failures through structured interviews with maintenance personnel. The results of these interviews (N=38) using the Human Factors Investigation Tool (HFIT) (Gordon, 2005) demonstrated that *Assumption*, *Design & Maintenance,* and *Communication* were the most frequent contributors to maintenance-related failures.

Based on the predominant factors identified in Study 2, a survey of the perceptions of maintenance personnel (N=178) was conducted for Study 3. Scales measuring *Problem-solving* (Morgeson & Humphrey, 2006) and *Vigilance* (Mann, Burnett, Radford, & Ford, 1997) were used to measure the processes that provoke assumptions. *Design & Maintenance* items from HFIT (Gordon, 2001), and scales from Wiio's (1978 a&b) Organisational Communication Development questionnaire (OCD/2) were used to test the factors identified in Study 2. Exploratory Factor Analysis indicated that the responses to the *Design & Maintenance* items loaded onto a single variable, while the *Communication* items loaded onto two variables, which were named *Job-related feedback* and *Information about change*.

The perceptions of personnel in lower and higher reliability work areas across the target organisation were compared using these scales, with reliability level ranked according to the monthly Mean Time Between Deferments of petroleum production. Significant between-group differences were found between work areas on *Design & Maintenance* and *Problem-solving*. These results suggest that better maintainability in the design of plant is predictive of higher reliability level. In addition, greater requirements for *Problem-solving* were associated with lower reliability level. There were no significant effects of reliability on *Vigilance* or either communication measure.

The quantitative data was triangulated with comments in response to an open-ended question asking about factors that help or hinder maintenance activities. Respondent's comments indicated that *Communication* was not significantly associated with reliability at the group-level. The reason appeared to be that *Communication* was an organisation-level property of the employing company. Many comments indicated that access to information was difficult, explaining the high occurrence of assumptions reported in Study 2. In addition, although maintenance personnel generally agreed in the survey that they were vigilant in decision-making, personnel in lower reliability facilities provided a higher proportion of comments indicating that the decision-making of supervisors and management had a negative impact on their work.

The results of the three studies support past research demonstrating that problem-solving skills (Tucker, 2002) and the design of socio-technical facilities (Reiman, Oedewald & Rollenhagen, 2005) have an important influence on organisational performance. The findings further extend research in the field of human factors by demonstrating a significant relationship between these two factors and group-level performance. The findings also demonstrated the importance of organisational communication, but as an organisational-level dimension that might not influence group-level measures. This research has implications for organisations that operate complex, hazardous technologies and that are attempting to improve organisational processes by utilising a human factors approach.

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1.0 Thesis Introduction and Overview

1.1 Introduction

Theory and practice in the fields of industrial maintenance, and engineering reliability have undergone significant development over the past decades. This has mainly concerned the effectiveness and efficiency of the organisations that manage hazardous technologies. In parallel with this have been the advances in research into human factors and organisational behaviour, which have improved the understanding of the role of humans in supporting the function of these organisations.

The knowledge gained from studying hazardous technologies has been in two principal domains: 1) knowledge about the processes that occur when machines fail, and 2) knowledge about the factors that create high reliability. For example, Reason (1997) estimated that approximately 50-70% of industrial failures involve a human element, including the Three Mile Island, Chernobyl, Bhopal and even the Barings Bank failures. While the characteristics of organisations regarded as High Reliability Organisations have been well-studied, less information is available concerning how humans maintain on-going reliability in other technology-intensive industrial workplaces. More needs to be understood about how successful functioning of equipment on a ‘day-to-day’ basis is achieved in those industries in which work is not as heavily regulated and proceduralised as it is in aircraft and nuclear power plant maintenance operations.

Aviation and nuclear power generation pose a safety risk to large numbers of people and to whole communities, and for this reason have been intensively studied. In other hazardous industries, such as petroleum production, there have been far fewer studies of the factors influencing safety and reliability. However, the financial criticality of petroleum production, the potential to injure workers, and the potential for environmental damage are still high, as recent events demonstrated in the disaster involving British Petroleum’s Deepwater Horizon platform (Urbina, 2010). The value of production for one company can be in the hundreds of thousands of dollars per hour, maintenance costs can be in the hundreds of millions of dollars per year, capital costs are often in the billions of dollars, and millions of consumers may be dependent on the continuity of supply. On this basis alone, the factors that influence maintenance reliability in the petroleum industry, including the human factors, would warrant attention.

Petroleum production, as with most modern industrial processes, relies on management by humans of complex control systems to maintain production at dependable levels and avoid dangerous operational states. Traditionally, the field of industrial reliability has concerned itself with technical solutions to inadequate maintenance performance and failures (Dhillon, 2002). However, even in engineering-oriented environments, recognition has emerged of the human factors underlying historical and potential failures (Pidgeon & O'Leary, 2000; Pate-Cornell, 1993). The growing body of research on the role of human factors in failures has demonstrated the importance of continuing to develop an understanding of the connection between the fields of organisational psychology on one hand, and engineering design and maintenance on the other.

The overall aim of the current thesis has been to address the need for a greater understanding of the influence of human factors on maintenance-related reliability in the unique environment of the petroleum industry. In order to more fully understand the origins of failures and the sources of reliability, an integrative approach was chosen in which a group-level measure for plant reliability was derived along with empirical measures of the human factors known to influence workgroup performance. Current theoretical frameworks for understanding human behaviour assisted in developing an understanding of these potential influences. The aim of the current thesis was to characterise the relationship between specific human factors and measurable maintenance outcomes in a petroleum industry context, in order to develop a more comprehensive understanding of the origins of reliable industrial performance.

1.2 Thesis Overview

Following this introduction, Chapter 2 is a review of theoretical and empirical research concerning reliability in a maintenance context, and the human factors that influence organisational performance. The literature is surveyed in order to provide an understanding of the relevant developments in the fields of engineering, organisational psychology, management, human factors, and industrial safety. In addition, developments specific to the petroleum industry are reviewed to provide background on the organisational context for the three studies in this thesis, which were all conducted within a single petroleum organisation.

Chapter 3 offers a rationale for conducting research aimed at identifying the human factors that promote failure or success in maintenance work. In addition to justifying the need for further research, the benefits in terms of developing the theory surrounding human factors in the workplace, and an appropriate methodology are discussed.

Chapter 4 describes Study 1, in which company incident reports were examined to identify the most-frequent human factors in maintenance failures. An evaluation of the methodology is provided, and the limitations of obtaining data from internal investigation reports are discussed.

Chapter 5 describes Study 2, which used a validated structured interview method to obtain detailed human factors information concerning past failures. The results from interviews conducted with maintenance personnel, and specifically, descriptions of the most frequently recurring contributing factors, are presented. Comparisons with the results from Study 1 are used to demonstrate the value of investigating the underlying organisational factors contributing to the occurrence of failures.

Chapter 6 discusses different ways in which the reliability of production facilities could be measured. This includes the standards by which engineering practitioners quantify reliability. The results of examining different reliability measures are presented, and one measure selected as the means of ranking the reliability level of different work areas within the target company, as needed for Study 3.

Chapter 7 describes the methodology and results, and provides a discussion of the findings obtained from Study 3. This study was designed to compare perceptions of maintenance personnel across nine production areas representing low, middle and high reliability facilities in each of three facility types. The survey measured perceptions of those human factors identified from Study 2 as being most frequently occurring in maintenance failures. The results are discussed, including the implications for addressing the positive and negative influences of human factors on the performance of maintenance workgroups.

Comments were also requested from the maintenance personnel who completed the survey form. These comments concerned their perceptions of the impediments to the conduct of reliable maintenance activities. In Chapter 8, a content analysis of the themes and super-ordinate themes in their comments is provided. The results of the qualitative analyses provided supporting information that aided in the interpretation of the quantitative analysis findings presented in Chapter 7.

Finally, Chapter 9 offers an overall discussion of the knowledge gained from the three studies. Significant findings of this thesis concerning the influence of human factors on maintenance reliability are reviewed. The investigations of human factors in failures, and the quantitative assessment of human factors in day-to-day reliability, are related to a theoretical understanding of the way that human factors impact on the workplace. In addition, the development and use of suitable measurement instruments for obtaining human factors and reliability data in the petroleum industry is discussed.

2.0 Literature Review

2.1 Introduction

In this chapter, a cross-section of the research in the human factors, organisational psychology, and management literature will be reviewed in order to understand how the role of human factors in maintenance reliability and in the petroleum industry are currently viewed. First, the literature relating to the concept of reliability in maintenance activities will be reviewed. Examination of the traditional engineering approach to reliability will be complemented by reviewing the research concerning the influence of human factors on maintenance tasks at the individual, group, and organisational levels. Consideration will then be given to the concept and requirements of a 'High Reliability Organisation' (HRO). The chapter will finish with ideas about the research required to understand the human factors that determine organisational performance in the maintenance of petroleum operations.

2.2 The Maintenance Task

In order to understand the way in which the reliability of maintenance activities develop in a petroleum industry environment, and in turn the role of humans in addressing the faults and limitations in industrial equipment, it is important to consider the nature of maintenance processes. The International Standards Organization (2006b) describes maintenance in an industrial environment as involving two essential types of activities, termed *corrective maintenance* and *preventive maintenance*. Preventive maintenance refers to "maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item" (p.7). The requirements for this are typically specified in routine preventative maintenance procedures, such as lubricating, adjusting, cleaning, and checking operating values. Some preventive procedures require a deeper understanding of the current state of the equipment, which can generally only be obtained through investigative processes termed condition monitoring (Moubray, 1997). Typically, condition monitoring includes detecting the extent of wear, vibration, excessive power consumption, leakage, or physical damage, which may in turn require corrective maintenance.

In contrast, corrective maintenance refers to restoring an item of equipment to a state in which it is able to perform its function, if it has been only partially functioning or has stopped functioning altogether (Moubray, 1997). This item can be as simple as a screw or as complex as an entire production plant. In either case, equipment ceases to function properly for a wide variety of reasons, including wear, corrosion, the deleterious effects of other components, and physical or electrical damage. It is the task of the maintenance technicians to determine what has failed and how best to repair the item in terms of available resources, such as time, budget, tools, spares, and expertise.

At times, maintenance technicians will have the benefit of detailed procedures (Bourrier, 1996) to provide guidance concerning the correct course of action. At other times, they may need to rely on past personal and industry experience to identify solutions. For this reason, corrective maintenance often requires similar activities as preventive maintenance, but a different cognitive approach, as a greater degree of problem-solving and decision-making is required to eliminate faults. An additional task that has been fundamental to the maintenance role, particularly in the aviation industry, is to not only correct a fault, but also to determine why it has occurred and to advise other interested parties of what has occurred in terms of both the problem and the solution. Boeing (Rankin, 2007) has facilitated this process within aviation companies by supplying software called the Maintenance Error Decision Aid (MEDA). MEDA was developed for recording and analysing maintenance incidents, and providing information to the industry on the means of addressing the causes of incidents (Latorella & Prabhu, 2000).

Aside from initial design, the performance of maintenance activities, and particularly the analysis of faults, will determine how reliably equipment, and in turn, petroleum production processes will perform. This concept of reliability is central to understanding the factors that influence the effective execution of maintenance tasks, and will be considered in the next section.

2.3 Concept of Reliability

Reliability is defined in theoretical terms (Sharma & Kumar, 2008) as "a measure of the probability for failure-free operation during a given interval" (p. 893). More empirically, reliability is expressed as a function of the mean operating time between failures, known as the Mean Time-To-Failure (MTTF) (Lewis, 1996). A concept related to reliability, concerning the effectiveness of maintenance in petroleum and other industrial operations is *availability* (International Standards Organization, 2006b). Availability refers to the percentage of time that a plant or item of equipment can fulfil its intended function, and is the inverse of the non-operating time experienced, known as *downtime*. Downtime can be either *planned* for maintenance activities or *unplanned* due to failures. Methods for applying these concepts to the measurement of the performance of plant and equipment are discussed in more detail in Chapter 6.

Measures of reliability, availability, and downtime provide a means for determining the effective use of production facilities, involving both the maintenance and operation of equipment. Krishnasamy, Khan and Haddara (2005) in their analysis of risk-assessment as a basis for maintenance strategies stated that:

> Profitability is closely related to the availability and reliability of the equipment. The major challenge for a maintenance engineer is to implement a maintenance strategy, which maximizes availability and efficiency of the equipment; controls the rate of equipment deterioration; ensures a safe and environmentally friendly operation; and minimizes the total cost of the operation. This can only be achieved by adopting a structured approach to the study of equipment failure and the design of an optimum strategy for inspection and maintenance (p.70).

Reliability as a focus for structuring maintenance activities was developed conceptually by Moubray (1997) in his widely adopted approach to plant maintenance, termed *Reliability-Centered Maintenance* (RCM). RCM is still considered a fundamental means of approaching the technical factors in industrial maintenance (Cheng, Jia, Gao, Wu, & Wang, 2008). Moubray defined RCM as "a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context" (p.7). In contrast, failures occur when equipment is "unable to fulfil a function to a standard of performance which is acceptable to the user" (p.9). Thus, reliability not only requires that an item of equipment carries out the functions for which it was designed, but that it also reaches a specified level of performance that is acceptable to the owner or operator.

Closely related to the concept of *reliability* is the concept of *process safety*. Research on process safety and reliability are enmeshed in part due to ambiguity in the usage of the two terms. Within industries viewed as high-risk, such as aviation, nuclear power production, and petroleum production, the terms *safety* and *reliability* are often used synonymously. For example, *safety* in these organisations generally does not refer to eliminating occupational injuries, such as 'slips, trips and falls' (McDonald, Corrigan, Daly, & Cromie, 2000). More often *safety* implies the *reliability of equipment*, that is, that the equipment carries out the function for which it was designed, and that the probability of failure-free operation is as high as possible. For example, reliability of an aircraft implies that it will not fail during flight, and hence will not endanger passengers, crews, or communities in its flight path. A factor in achieving this is the performance of maintenance and operational crews (Salas, Burke, Bowers, & Wilson, 2001; Salas et al., 1999).

The occurrence of failures then implies lower reliability and a reduction in the level of safety. Latorella and Prabhu (2000) examined a number of issues relating to aviation safety, focussing mainly on human errors that have been linked to fatal crashes. The same analysis included maintenance-related issues of efficiency, in which maintenance errors required aircraft to turn back, return to the gate, or be otherwise delayed. In Latorella and Prabhu's discussion, *safety* was linked to reliable outcomes from maintenance activities. Similarly, in discussing nuclear power plant *safety, Pyy* (2001) studied the impact of various types of maintenance-related failures on plant operating systems, such as instrument valves. Safety in this context particularly relates to the reliability of the safety systems designed to prevent loss of coolant, reactor fires, or release of radiation, as occurred in the Chernobyl nuclear reactor accident (Munipov, 1992). The issue of process safety, whether in aviation, chemical processing, or petroleum production, is therefore closely related to the dimension of reliability.

2.4 Cost of Unreliability

As Cooke (2003) contends, "the nature of maintenance work has changed as a result of a huge increase in the number and variety of physical assets to be maintained, increasing automation, and complexity" (p. 239). As a result, in the petroleum industry, a considerable portion of budgets is devoted to the maintenance of the large number of items of processing equipment, operating in both marine off-shore and on-shore environments. For example, one petroleum production company estimated that ~30% of their operating budget was expended on maintenance, accounting for $174.8 million in 2006. Eti, Ogaji and Probert (2006) estimated that 40% of the cost of energy generation could typically be attributed to maintenance processes, but that this figure is up to 15% lower in better-performing organisations.

In addition to these high costs associated with repair and servicing of production equipment, loss of production due to breakdowns, or unplanned maintenance downtime associated with the maintenance process, also represent a significant cost to the organisation. An indication of the value of maintenance-related losses in production can be derived from production figures for a large petroleum gas plant. For example, Exxon Mobil's Longford Gas Plant near Melbourne, Australia can produce 1000 TJ/day of Liquefied Natural Gas and 8M litres/day of Liquefied Petroleum Gas (Victorian Government Department of Primary Industry, 2009). At current commodity rates, this equates to approximately US$225,000/hour, which could be lost as a result of a failure affecting a critical area of production. On-going losses at this rate will affect commercial performance and ultimately the viability of the company. Aoudia, Belmokhtar, and Zwingelstein (2008) examined the consequences of poor maintenance management in petroleum operations using interviews, questionnaires, and audits. They found that although planned maintenance accounted for only 2% of unproductive time, unplanned maintenance accounted for 66% of unproductive time. The cost to the company of this unreliability was equivalent to a 13% reduction in sales, not counting the indirect costs of ineffective maintenance, such as higher consumption of spares and damage to reputation.

The effects of poor maintenance extend beyond lost production income for the company involved. Sovacool (2008) estimated that total property damage due to infrastructure accidents in the petroleum industry from 1907 to 2007 amounted to US$ 10.1 billion. For example, losses to the Western Australian state economy resulted from an explosion on 3 June 2008 of the gas installation on Varanus Island, Western Australia. The explosion was the result of a gas leak due to a failure to conduct maintenance inspections of a critical pipeline. The ensuing explosion caused loss of gas production for four months, representing 30% of the state's gas supply. The total loss to the state economy was estimated at between A$120 million and A$2.4 billion (Senate Standing Committee on Economics, 2008), depending on which impacts were included. Another example of the high cost of a maintenance failure in a petroleum facility is the Piper Alpha oil platform disaster on 6 July 1988 that led to the loss of 167 lives and a financial loss to the company of US$ 3 billion. Altogether, Sovacool (2008) estimated that 3,330 fatalities had resulted from infrastructure accidents in the petroleum industry from 1907 to 2007.

The outcomes of a lack of reliability in maintenance are reduced performance of equipment, poor control over processes, and risk of financial and human losses. Out of these losses developed a recognition of the need for maintaining a high degree of reliability, and the need for interventions to improve the maintenance of systems that were required to be as close to 100% reliability as possible (Hollnagel, 2006). The following discussion is an examination of theoretical and empirical research into the dimensions of high reliability relating to the task of maintenance in petroleum operations.

2.5 Determining Reliability in Maintenance Operations

As described above, the consequences of loss of reliability and control over processes have resulted in a range of adverse impacts on production processes (Pidgeon & O'Leary, 2000) as well as injuries to humans. Both disruptions to production and injuries to people represent costs which organisations hope to avoid by determining reliability requirements. As Reason and Hobbs (2003) discussed, past disasters demonstrated the need for organisations to maintain control over systems and processes, and manage human performance, in order to achieve reliability in maintenance. However, this often does not happen, as Lofsten (2000) found in examining the maintenance approaches of eight Swedish companies. Although maintenance efficiency in operations was monitored, they rarely measured reliability, and so were not able to address the potential for failure and the consequent potential for the losses described above. He argued for the need for a measure of the effectiveness that maintenance inputs had on the reliability of production. Researchers in the energy field (Eti, Ogaji, & Probert, 2006) also expressed the need for performance measures of "both effectiveness (doing the right things) and efficiency (doing those things right)" (p.306).

However, as Cooke (2003) argues in relation to manufacturing firms, "What is lacking in the maintenance regime is to develop a far more rigorous maintenance strategy to look into improving the long-term reliability of the equipment" (p.242). In addition to a lack of a maintenance reliability strategy, another problem with determining reliability is the time lag that often occurs between performance of maintenance activities and observable outcomes. A study of nuclear reactor incidents (Svenson & Salo, 2001) found that 40% of serious errors requiring *licensee event reports* could remain undetected for more than 10 weeks. Thus, operations may experience a progressive reduction in the reliability of maintenance, with no indication of a need for corrective action before a major incident occurs. Given that reliability encapsulates the ability of operations to continue to operate without failures, researchers such as Øien (2001a) sought ways to determine the risks to reliability in the activities of petroleum industry operations. In Øien's approach to reliability, he conceptualised the relationship between maintenance activities, reliability, and risk to production performance in his *Organisational Leak Model* (Figure 1).

In this model, a number of factors are seen to impact on the corrective and preventative maintenance processes described in Section 2.2. This includes initial design as well as factors relating to the individual (e.g. training and competence), workgroup (e.g. planning) and the organisation (e.g. procedures and organisational control). These in turn impact on the physical condition of the plant (e.g. valves and instrumentation) which then influence Øien's measure of petroleum plant reliability, namely the frequency of leaks. Sklet (2006) further estimated that from 2001 to 2004, 40% of these oil and gas releases were due to errors in manual work, such as maintenance, indicating the relevance of this model to reliability.

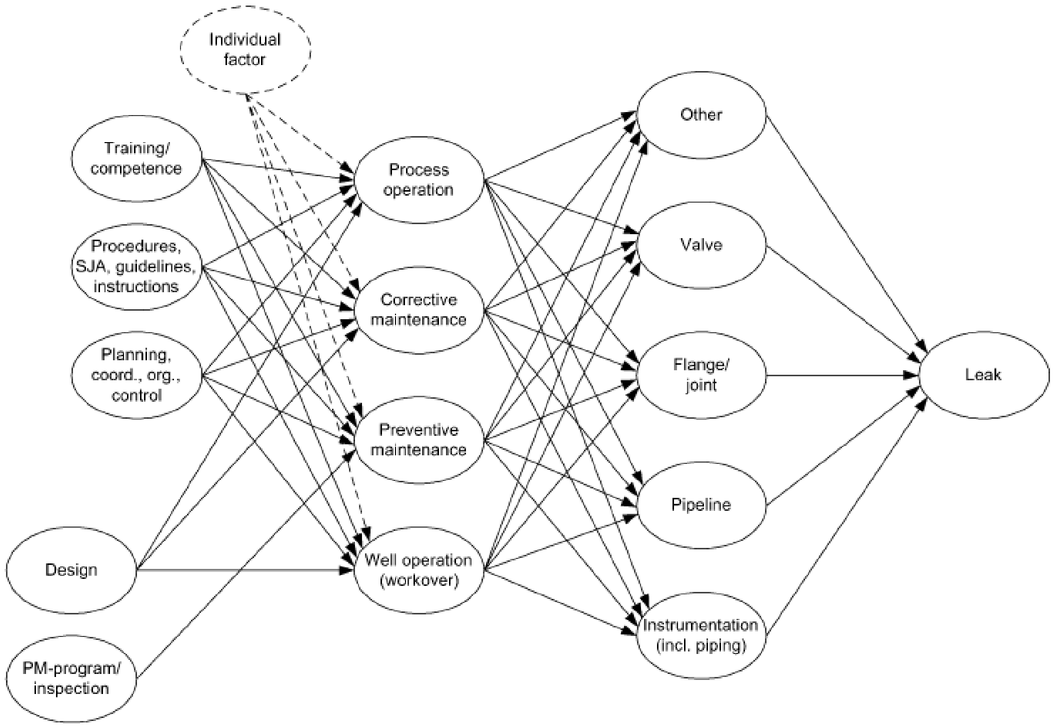

Figure 1. Petroleum organisation reliability model (Øien, 2001a)

Although the adverse impacts on production and their causes may vary depending on the organisational context, Øien's approach represented a means by which companies could determine reliability based on the various risks to processes occurring within their operations.

2.6 Engineering Approaches to Improving Reliability

As a consequence of understanding the value of reliability in industrial operations, many researchers have focussed on methods for improving reliability (Saleh & Marais, 2006; Thomas, 2005; Vanderhaegen, 1999). As failures were often viewed as faults in equipment, processes, and technologies, the approach to improving reliability was consequently viewed as a technical task, typically based on engineering methodologies (Lewis, 1996; Reinach & Viale, 2006; Scarf, Dwight, & Al-Musrati, 2005). Engineering methodologies relied on making technical changes in order to *re-engineer* processes and technologies that were viewed as faulty or failure-prone (Wang, 2002; Zequeira & Berenguer, 2006). These 're-engineering' methodologies typically involved technical audits (De Groote, 1995), engineering risk assessments (Kadak & Matsuo, 2007), and design improvements to re-work equipment layouts, processing stages, engineering specifications, and physical inputs to processes (Kinnersley & Roelen, 2007). Technical designs and engineering specifications were thus considered to define the *potential* production output for a particular operation.

The *actual* productivity of an operation was considered to be subject to a range of risk factors that might impact on the reliability of critical processes, as shown in Øien's model (Figure 1). From an engineering frame of reference (Bamber, Castka, Sharp, & Motara, 2003), most of the risk factors encountered in production appear to be concerned with the technical limitations to achieving the potential production output. Bamber et al. discuss the concept of *Overall Equipment Effectiveness* as a measure of plant performance that is a function of 1) the time a machine is available, 2) the rate at which it operates compared to its design rate, and 3) the quality of its output. A machine's *Overall Equipment Effectiveness* is impaired by technical factors, such as wear, corrosion, leaks, power outages, production bottlenecks, and shortages of spare parts. Research in the various fields of reliability engineering has focussed on the development of technical concepts and reliability models concerning the probability and consequence of these risks eventuating (Dhillon, 2002). For example, Krishnasamy, Khan, and Haddara (2005) considered risk-based maintenance methodologies in which maintenance activities were determined by the probability of a component or machine failing. Again, risk assessments were only based on the probability of technical faults occurring. These methods generally relied on the failure rates being known and constant. Todinov (2004) examined the commonly accepted reliability measure of Mean Time-to-Failure (MTTF), and considered that it was only applicable to repeating failures, as in the case of components that wear out at a relatively constant rate. He argued that, in its basic form, MTTF is difficult to apply as a reliability measure in situations in which failures occur randomly, as in the petroleum industry. As an alternative, he suggested that the Minimum Failure-Free Operating Period was a better measure of reliability, as it provided a better indication of when preventative maintenance was required. Different measures of reliability and risk will be discussed in more detail in Chapter 6.

Tixier, Dusserre, Salvi, and Gaston (2002) reviewed 62 different methods of risk analysis devised for industry. They found that these analysis methods were designed to 1) identify risks based on activities and equipment, 2) evaluate the damage consequences or the probability of the risk, and/or 3) rank the risks so that the most severe risks are corrected first. Methods, such as Reliability-Centred Maintenance, Failure Modes and Effects Analysis (FMEA), and Fault Tree Analysis (FTA), have been developed as a basis for identifying all technical risk factors related to past and possible future failures (Lewis, 1996; Sharma & Kumar, 2008). In each of these methods, the objective is to identify as many existing mechanisms of failure (e.g., FTA) or potential modes (e.g., FMEA) as understanding of the technology allows. In this way, the engineering approach to reliability commonly involves using risk analysis techniques to capture all known and suspected causes of technical failure in a particular piece of equipment or a system.

Following this approach, researchers in the petroleum industry such as Øien (2001b) have developed structured methodologies for reducing operational risk and improving reliability through maintenance effectiveness. Øien developed a quantitative risk analysis model to characterise the technical 'risk influencing factors' that increase the potential risk (e.g., 'probability of ignition due to drive unit') and those that reduce the potential risk (e.g., 'number of drillings and completions'). The overall risk to reliability can then be calculated from the mathematical interaction of these probabilities of failure. Insight into the current approach to reliability in industry can be gained by examining advertisements for Reliability Engineers. In one advertisement (TiWest Joint Venture, 2007), the stated aim was to develop maintenance strategies and use "analysis of equipment and components to improve plant availability and reduce cost and ensure compliance to statutory standards" (p. 19). Characteristically, the advertisement did not indicate recognition of the role of the humans charged with the task of maintaining this equipment and componentry. The engineering approach involves addressing as many of these technical mechanisms as is practically possible and economically justifiable. Although non-technical factors could be considered in these techniques for risk analysis and reliability measurement, in practice the engineering approach generally involves understanding the technical risk factors in order to improve the technology used.

2.6.1 Efforts to improve reliability through maintainability

A part of the engineering approach to improving the reliability of technology involves ensuring that the technical design of equipment facilitates on-going maintenance, a dimension referred to as *maintainability*. The International Standards Organisation (2006a) defines maintainability as the:

> Ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources. (p. 15)

Thus, the implication of this concept is that the maintainability of an item of equipment is a function of its inherent ability to be maintained, i.e. its original design, and specified maintenance procedures (Mason, 1990). These maintenance procedures are further defined (International Standards Organization, 2006a) as the "combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function" (p.17). Meanwhile, regarding this inherent design, the standard states:

> The design of an item shall ensure three things, namely:
> a) that it achieves the performance required of it
> b) that it is reliable
> c) that it is maintainable.
>
> The second and third of these characteristics directly affect the maintenance effort which shall be expended on an item in that the achieved reliability reflects the frequency of unscheduled maintenance and the maintainability reflects the effort necessary to undertake all maintenance.
>
> Therefore actions performed during the design of an item and intended to affect the failure rate and the severity of the failures call mainly for reliability techniques, but those intended to affect the preventive and corrective maintenance and the duration, cost, and support requirements of maintenance tasks call mainly for maintainability techniques. An item that can be maintained easily and is supported by a competent and efficient maintenance organization has a greater availability and a reduced life cycle cost than one that does not have these attributes. (pp. 17-19)

The implication of these examples is that, despite an acknowledgement of the role of the maintenance organisation, it is the quality of engineering design that will dictate the requirements for ‘competency and efficiency’ of maintenance personnel and maintenance strategies. This is also reflected in the hope that maintainability can be designed into the equipment from the start, as described in the section of the International Standards Organization standard (2006a) entitled *Statement of Maintainability Requirements*, “Maintainability should be specified in such a way that the designer has a clear understanding of the need for maintenance and the manner in which the item is to be supported” (p. 25).

Despite this recognised need for improved maintainability, Tjiparuro and Thompson (2004) argued, “maintainability evaluation methods are characterized by their fragmentation and lack of standardization, a factor that will contribute to their difficulty of implementation at design” (p. 105). They suggested simplifying designs and improving labelling of parts as basic steps to improve the maintainability of equipment, contending that “ the possibility of introducing the wrong components or making incorrect adjustments is an area where poor maintenance can lead to reliability problems” (p.111). Therefore, although it may be reassuring for technically-focussed organisations to believe that proper designs currently ensure that systems are both maintainable and reliable, this has not been supported by the evidence. The examples mentioned above of serious technical failures of engineered systems and the complexities of ensuring maintainability indicate that an engineering approach that relies exclusively on technical factors may not be capable of reducing the risk of failure.

2.7 Failure of the Engineering Approach

2.7.1 Engineering design flaws

In the Piper Alpha oil platform disaster mentioned above, Pate-Cornell (1993) traced many of the failure mechanisms back to the design of the platform. Although she highlighted a number of organisational issues as being responsible for creating the potential for a disaster, she concluded that it was the ‘couplings and dependencies’ between systems that led to events spiralling out of control. These couplings included the dependence of safety systems on the main power supplies, proximity of emergency control systems to production equipment, and the grouping together of alternative escape facilities. In addition, *common-mode failures* were not considered in the design, namely, those situations in which several emergency systems failed through a single, common cause. Pidgeon and O'Leary (2000) contended that in many failures, the designs did not provide for complex, unexpected interactions within and between systems.

The role of engineering design in failures in process industries, such as in petroleum and chemical plants, was further supported by data (Taylor, 2007) that 55% of the accidents in chemical industries were the result of design errors. In the cases of reactor incidents, in which 46% of the errors made in incidents with nuclear reactors were related to design, Taylor listed among the causes of design error: oversights, unknown effects at the time of design, overlooked interactions, and communication problems. Kinnersley and Roelen (2007) arrived at similar figures for design-related accidents, i.e. 51% for aviation and 46% for nuclear power generation. However, as they explained, considerable understanding of the processes involved was required to determine whether or not design was a root cause of an accident, and other confounding issues might in fact have contributed to accidents, particularly with regard to operational procedures not intended by the designer.

In their discussion of the interventions preceding the Challenger space shuttle disaster, Starbuck and Milliken (1988) postulated the reason why many engineering processes actually increased the probability of failure. They called this a 'fine tuning' process in which "successes may induce engineers and managers to attempt to fine-tune a socio-technical system - to render it less redundant, more efficient, more profitable, cheaper, or more versatile. Fine-tuning rarely raises the probability of success and it often makes success less certain" (p.323). In effect, systems have been engineered to the point at which control became more difficult, despite so-called 'better designs.' This and discussion of other accidents provided evidence of the paradoxes inherent in resolving problems exclusively through an engineering approach.

Heimann (2005) used a further analysis of space shuttle accidents, as an example of why technologies experienced repeated failures. Designs were presumed to be "well-defined, precise, and objective applications of technical knowledge" (p.110).

However, his investigations of technical failures revealed that there was in fact considerable ambiguity, deviation from specifications, and the need to make decisions without complete knowledge of the true situation, which effectively amounted to a loss of cognitive control. Heimann then went on to say that technical failures continued to occur because organisations have continually tried to decide how to allocate resources to prevent failure, but lacked knowledge about the true state of their systems. They believed that they understood their systems well enough to control them, but he contended that control also required understanding of the non-technical influences. This was demonstrated by the Deepwater Horizon explosion and oil spill in the Gulf of Mexico on 20 April 2010, which was attributed (Urbina, 2010) not to the design of the rig, but to bad decisions, unheeded warning signs, compounding of small lapses, and "exceptions to rules [that] allowed risks to accumulate and made disaster more likely on the rig" (p.A1).

As Bea (1998) argued, engineering practitioners have not sufficiently concerned themselves with the support systems needed for engineered structures, such as the non-technical systems for maintenance, warnings, communication, and information. More significantly, he contended that engineers have also not developed the human systems needed to cope with the evolution of critical failures of technical systems. If this is the case, then the occurrence of failures identified in the studies described above as 'design errors' may not be the cause of failures, but rather a symptom of not recognising the role of non-technical factors in technical systems. These non-technical factors include the involvement of humans in constructing, selecting, operating, and maintaining the equipment and processes on which engineered systems rely. For example, despite engineering improvements in the mining industry, Tomlingson (2005) estimated that since the 1970's, maintenance activities have *risen* to 35% of mining costs and that "unnecessary downtime continues to threaten mining performance" (p.54). He suggested that a major part of this is due to a failure of other departments to support the activities of maintenance personnel. In theory, the efforts to engineer reliability and maintainability should over time have led to reliability improvement, and overall maintenance and downtime reductions. By utilising technical investigations and design improvements, the causes of failure in a particular technology should have been progressively eliminated. However, in practice, the indications are that unnecessary costs and failures are not being eliminated. Ultimately, flawed technical designs may be only one consideration in failures of engineered systems, with a lack of support for humans working with those designs being an equally important consideration.

2.7.2 Nature of problems highlights the non-technical issues.

In regard to design-related failures, Kinnersley and Roelen (2007) commented on the need to widen the scope of determining the causality of failures:

> The observation that design issues were causal or contributing to the accident does not mean that other factors (such as human factors, operational procedures, maintenance issues, etc) did not play a role. (p.34)

Similarly, in a study involving 200 Offshore Installation Managers across the North Sea Petroleum Industry (O'Dea & Flin, 2001), many were of the opinion that the focus needed to change from technical and design issues to leadership, communication and employee motivation. That is, in terms of operational reliability, technical design had not produced the required outcomes, and management believed that refocusing on managing workforce behaviour was necessary. In addition to the design issues mentioned above in the Piper Alpha oil platform explosion, Pate-Cornell (1993) also attributed the failures to "inexperience, poor maintenance procedures, and deficient learning mechanisms" (p.232). Therefore, it was not only the continuing occurrence of technical failures in complex systems that indicated to researchers that a change in paradigm was required, but also the recognition of the nature of these failures.

The problems inherent in retaining control over systems in which humans interact closely with technology, termed *socio-technical systems,* was studied by Brehmer (1993). He attributed loss of control in these systems to the understanding that modern technical systems were 'complex, opaque, and dynamic.' Specifically:

- the complexity of tightly-coupled processes can involve conflicting goals
- there are limitations to how much of these systems can be observed, and
- these systems are changing, both by themselves and through organisational interventions.

In Rasmussen's (1997a) pioneering work on technical risk as a matter of *loss-of-control* at the boundaries of safe operation, he reviewed the main non-technical factors that contributed to the Zeebrugge shipping accident. In this analysis of the Zebrugge capsizing, he observed that system design and decision-making were based on risk models of each of the systems involved (e.g. harbour design, cargo management, passenger management and vessel operation), without considering interactions between the separate systems. His conclusion was that performance in complex system is better-controlled by making the boundaries of safe operation clear, and improving the coping skills of the workforce needed in situations in which control might be lost. This shift in focus occurred with the conceptualisation that reliability depended on *control* of systems, in addition to *design* of systems. As mentioned previously, design serves to determine potential performance, but systems researchers such as Rasmussen (1997a) and Hollnagel (2002) considered that actual performance depended on the degree to which technologies are under control in terms of their initial design, regulation, and maintenance. Once this idea was introduced, there was an attendant recognition that non-technical, as much as technical, factors determined how well a system could be controlled.

Finally, Munipov (1992) provided insights into the political and cultural factors behind the accident in the Chernobyl nuclear power plant (NPP). He reviewed all of the apparent failings of the USSR's nuclear industry, including that of the technology used. Despite a thorough review of "problems due to the inadequate design of the reactor and absorbing rods" (p.339), he still concluded that "inadequate human-machine interactions" were the main cause, quoting V. Konovalov, the Minister of Nuclear Power and Industry, as saying that, "Even the most effective sophisticated safety control system will fail to provide for plant reliability if human factors are not taken into account" (p.341). Munipov's contention was that, despite the focus on the extant technical deficiencies, the human factors in which humans interact with machines and systems were the ultimate determinant of the reliability of the technical systems at Chernobyl.

Part of the engineering literature reviewed above presented reliability as an exclusively technical matter, often with what Schein (1996) refers to as a "preoccupation with designing humans out of the systems" (p. 14). There was a belief on the part of these researchers that through engineering studies, failure investigations, and the setting of appropriate design standards, improvements in design could prevent failures. At the same time, there has also been recognition in other literature, particularly in the body of research aimed at investigating and understanding disasters involving technical systems, that human factors will continually feature in these failures. It has become apparent to some researchers (Cooke, 2002; Dekker, 2005) investigating modern industry, that no amount of design change or technical strategy development can obviate the need for resolving the issues relating to human-machine and human-systems interactions in the workplace. Hence, to understand the influences on the reliability of petroleum maintenance, it is necessary to review the literature concerning these human factors and examine their relevance to maintenance effectiveness.

2.8 Human factors in Organisational Reliability at the Individual Level

2.8.1 Human factors at different organisational levels

Based on this recognition that human factors may play an important role in maintenance reliability, the following sections review the literature relating to the human component of systems in the workplace, and particularly the role of maintenance personnel responsible for the reliability of petroleum production systems. As Figure 1 indicated, a range of individual, workgroup, and organisational factors influence petroleum maintenance activities, which in turn affect physical production systems and ultimately performance outcomes. Many researchers (e.g., Torp & Grøgaard, 2009; Zohar & Luria, 2005) have recognised that organisational phenomena should be conceptualised and investigated at the individual, group, and organisational levels in order to properly understand the mechanisms involved. Their research differentiated the effects of phenomena at each level, as well as the effects of factors operating at one level on another level. Therefore, the following examination of human factors in the maintenance workplace will consider each of these levels in turn, beginning with the individual level, in order to reflect current theoretical frameworks.

2.8.2 Human error

At the individual level, considerable research attention has focussed on the occurrence and causes of human error in maintenance activities. Sklet (2006) estimated that 40% of oil and gas releases could be attributed to human errors in manual work. Lorenzo, Vanden Heuvel, and Rooney (2006) quoted a figure of 41%

for maintenance and operator errors in petroleum refining and processing, arguing that "human errors have been significant factors in almost every accident, equipment shutdown or quality problem" (p.28). Regarding other industries, Reason and Hobbs (2003) discussed the issue of managing human errors in maintenance quoting an estimate that 42-65% of the human performance problems in US and Japanese nuclear power plants are associated with maintenance errors. In aviation, Shappell (2000) estimated that 70-80% of aviation accidents involve human error to some extent. These errors may relate to the design of the aircraft, operation by aircrew, or maintenance of aircraft. However, he maintained that "to attribute accidents solely to aircrew error is like telling patients they are simply 'sick' without examining the underlying causes or further defining the illness" (p. 1). Furthermore, he contended that aviation accidents typically have multiple contributing causes, with human error merely being the last, and not necessarily even the primary, cause.

Early in the history of psychology, William James (1890) began studying the dimensions of human cognition that played a contributing role to human error, including attention and memory. By the 1950s, Hughes (1951) propounded a more specific approach to mistakes in the workplace based on the need to reduce and absorb the risk of error, mistakes and failures. He discussed two issues in particular reflecting the origins of human error and its causal role in work-related failures. Concerning what he called a 'jurisprudence of mistakes', he raised the notion that a "colleague-group will consider that it alone fully understands the technical contingencies" involved in a job and has "the sole right to say when a mistake has been made" (p.323). In essence, he considered that an action that was judged to be an error in hindsight might well have appeared logical at the time. He also examined the role of *art, cult, and ritual* as being not only a basis for professional practice, but also connecting tasks "to the social system in which the work is done" (p.325). In addition, he considered that art, cult, and ritual provided "organisational checks and balances against both the subjective and objective risks of the trade" (p.325). These are the risks that are inherent in doing a particular job. Altogether, Hughes' writing represented an early attempt to explore work-related errors as symptomatic of the non-technical dimensions of the workplace, and not just as a label to explain why a technical system has failed.

In more quantitative research into reliability as an issue involving human performance, the relationship between humans and machines was explored through various methods of Human Reliability Assessment (HRA) (Kirwan, 1994). Cacciabue (2000) reviewed the forms of HRA that had been developed, comparing the earlier method of the Technique for Human Error Rate Prediction (THERP) with Human Error Risk Management for Engineering Systems (HERMES) and the Dynamic Logical Analytical Method (DYLAM) (Cacciabue & Cojazzi, 1994). The DYLAM approach was an attempt to integrate the probabilistic nature of component failures with the probabilities of human error. All of these methods were aimed at statistically quantifying human failure rates in the same way that machine failure rates were calculated, for example as the Mean Time To Failures (MTTF) of components (Lewis, 1996). This approach was applied to calculating probabilities of human error in petroleum operations (Khan, Amyotte, & DiMattia, 2006), using the Human Error Probability Index (HEPI), which was based on the Success Likelihood Index Methodology (SLIM) developed for the US nuclear industry. The HEPI method incorporates Performance-Shaping Factors (PSFs) relevant to offshore operations based on expert judgements, where probability data on human error rates are not available. PSFs are factors related to task execution that influence outcomes, such as stress, complexity, training, and experience in the study of Khan et al.

The advantage of the HRA techniques was the ability to quantify the probability of human failure occurring, and to add this mathematically to the probability of machines failing, in order to produce an overall probability of failure. For many industrial processes, the overall risk of failure is a useful measure. However, in order to accomplish this form of analysis of human error rates, human errors needed to be treated generically, requiring different types of errors to be grouped together. Foregoing Hughes' (1951) 'jurisprudence of mistakes' in order to quantify these mistakes meant sacrificing an understanding of the qualitative differences between human actions. Without this understanding, the task of eliminating the sources of unreliability may be more, rather than less complicated.

2.8.3 Characterising human error

In contrast to the HRA approach, many researchers have concerned themselves with differentiating between different types of errors by monitoring and categorising the 'risks of the trade' that occur in various industries, such as petrochemical (Kariuki & Löwe, 2007), aviation (Hobbs, 2000) and nuclear power production (Pyy, 2001). Kariuki and Lowe developed a taxonomy of human failures to complement the categorisation of equipment failures for use in a Process Hazard Analysis, which is used to determine the potential contributors to a process-related accident. The human factors that they considered as contributors to the occurrence or reduction of errors were:

- Organisation (e.g., organisational learning and supervision)
- Information (e.g., communication, training, and procedures)
- Job design (e.g., staffing and work schedules)
- Human system interface (e.g., design of controls)
- Task environment (e.g., lighting)
- Workplace design (e.g., accessibility)
- Operator characteristics (e.g., attention/motivation)

Similarly, in commercial aviation, studies of human error have been conducted to develop taxonomy based on 1) PSFs (Latorella & Prabhu, 2000) such as access, visibility, and judgement interference, and 2) the most common error-provoking conditions in maintenance tasks, which Hobbs and Willamson (2003) identified as time pressure, poorly-designed equipment, inadequate training, and poor coordination and communication between workers. Having developed an appropriate taxonomy, the potential for errors to occur can then be managed by differentiating between the various PSFs and error-provoking factors in the workplace, and devising appropriate mitigation interventions (Reason & Hobbs, 2003).

Two conceptual developments in the understanding of human factors in the workplace have come from these taxonomies of error. Reason (1987; 1997) devised a typology of errors that distinguished among the different cognitive bases for human failings. His typology of 'slips, lapses, mistakes, and violations' differentiated errors on the basis of both the *intention* of an action, as well as the *intentionality* of the outcome of incorrect actions. Thus, an incorrect action may be intended or unintended, and equally the outcome may be unintended or intended. Each of these possibilities results from a different cognitive and motivational process. Rasmussen (1982) further contributed to an understanding of the cognitive origin of errors with his Human Malfunction model, using what he termed a *multi-facet taxonomy* to describe the causes of human error. He described a hierarchy for human errors as being *skill-based, rule-based,* or *knowledge-based.* By characterising the type of cognitive activity that was occurring at the time an error was committed, it was then more effective to devise a task-related strategy for avoiding recurrence.

The error classifications developed by Reason and Rasmussen described above have provided a basis for further development of frameworks for empirical analysis of the relationship between human actions and unintended failures. For example, a significant finding in Hobbs and Williamson's (2002) study of critical incident reports obtained from aircraft mechanics concerned the relative prevalence of rule-based errors in comparison to knowledge-based and skill-based errors. The work demands for mechanics, who were not supervisors, entailed mainly skill-based tasks (65%) with a lesser number of rule-based (31.5%) and knowledge-based (3.5%) task demands. However, a review of 101 incident reports indicated that the highest ratio of errors to task demands occurred for knowledge-based tasks (2.03) though the overall proportion of these errors (7%) was low. The percentage of skill and rule based errors was approximately equal (~46%). This meant that the ratio of errors to task demands for rule based tasks was more double that of skill-based tasks, i.e. 1.5 compared to 0.7. They concluded that knowledge-based activities, such as *diagnose or decide* (detection and decision-making) and *functional testing* (problem-solving), involved the greatest risk of error. However, their results suggested that the greatest opportunity to reduce the absolute number of errors in a similar maintenance workplace would appear to be in the category of tasks based on rules. This has important implications for both the analysis of the contributors to maintenance failures, which they describe elsewhere (Hobbs & Williamson, 2003), as well as the interventions that might be implemented to mitigate the occurrence of errors.

Although errors remain an important consideration across all industries, several of the pioneers in human factors have come to regard errors as no more than indicators of more fundamental individual and organisational processes. Rasmussen (1990) considered errors as an inevitable outcome of decision-making within the complex constraints of a modern socio-technical operation. He defined errors, when they occurred, as a 'link in the chain' of events informed by fundamental organisational processes. He argued that they should not be considered evidence of the fallibility of humans as a root cause of unreliability, and instead concluded with the *caveat*:

> Work in modern, high-tech societies calls for a reconsideration of the notion of human error: research should be focused on a general understanding of human behaviour and social interaction in cognitive terms in complex, dynamic environments, not on fragments of behaviour called *error*. (p. 1198)

Therefore, it is important to bear in mind that, although human error is frequently identified as the primary or even the only non-technical factor in a particular failure, it can at most be considered a starting point in any analysis of the contributors to a failure. The concept of identifying these contributors more holistically will be examined in greater detail in Section 2.11.1.

2.8.4 Procedural violations

Lawton (1998) suggested that training could reduce the occurrence of errors, but not the incidence of violations. Similarly, Reason, Manstead, Stradling, Baxter, and Campbell (1990) considered violations fundamentally distinct from errors; that is, although errors and violations are both individual-level phenomena, violations unlike errors are defined by the social context, e.g. procedures, social norms, and perceived expectations of peers. In a study of self-reported errors and violations among drivers, they found that the occurrence of violations was distinctly different to that of errors. Their data indicated that violations were moderated by different motivational factors, gender differences, and what they termed 'over-engagement' of the individual. Also, in contrast to errors, which have an entirely negative connotation, they reported that some high-violation groups studied could actually perform more effectively due to a better-developed ability to process information. For example, they quote a study (Fergenson, 1971) in which some car drivers were found to have lower vehicle accident rates, despite being classed in the high-violation group. Controlling the intentional violation of rules, procedures, and behavioural norms potentially offers organisations a more effective means of influencing outcomes than trying to control unintended errors.

In aviation, Collier (2004) reported that in an analysis of US National Transport Safety Board records of adverse aviation events in which maintenance was implicated, *failure to follow procedures* was a factor in 76.5% of events, compared to 15.2% for *errors and omissions*. Reason, Parker, and Lawton (1998) considered that the structuring and imposition of rules and procedures was the principal mechanism that organisations had for regulating behaviour in the workplace. For this reason, the underlying motivations and the circumstances under which violations of rules and procedures occurred have been of particular interest to hazardous industries, such as petroleum production (Hudson, Parker, Lawton, & van der Graaf, 2002). Managing rule-breaking has been cited as an important element in a program for avoiding safety incidents in the petroleum industry (Hudson, 2007). In further consideration of workplace behaviour, Reason, Parker, and Lawton (1998) identified 10 ways in which employees behave in relation to compliance with procedures. These behaviours were dependant on organisational and motivational issues, such as the existence and appropriateness of an applicable procedure for the task concerned, whether the outcome was successful, and whether the behaviour was 'psychologically rewarding'. These underlying factors led to the categories of behaviour in their taxonomy, such as *Correct Improvisation* and *Incorrect but Rewarding Violation*. This taxonomy provided a means by which organisations could evaluate employee reactions to existing procedures. Thus, in hazardous industries, Reason, Parker, and Lawton (1998) argued that the cognitive rationale for violations was as much of a concern as the fact that violations were being committed, as in the case where "variations in the local circumstances negate the applicability of the available rules" (p.301).

Reason et al (1998) proposed that the solution to this apparent conflict between rules and behaviours, and the complexity of situations with which workers must work, did not lie in more procedures. They recommended developing a better balance between the available control mechanisms, based on awareness by supervisors of local constraints to rule compliance. Fewer process or administrative controls were required, to be replaced by a greater emphasis on controlling output. Output control, in comparison to fixed rules, would be more closely related to the organisation's immediate goals, and relied on self-imposed group-level and individual level control. Effectively, they contended that workers must be allowed to make workplace decisions based on their abilities in risk perception, while bearing in mind that allowing employees to make what they referred to as *optimising violations*, i.e. breaking rules for their own benefit, created a climate in which rules become devalued. A related finding by Lawton, Parker, Manstead, and Stradling, (1997) was that violations of road rules were more commonly associated with positive affect, indicating that for the individual, violating rules would not necessarily be experienced as negative behaviour. This corresponded with the violation category, *Incorrect but Rewarding Violation*.

Lawton (1998) later applied this knowledge gained from car drivers to a study of railway shunters. She described the categories of violations involved, as well as the underlying reasons for committing them. In terms of self-reported motives for violating rules, she found three common pairs of factors: attitudes and motivation, situations and control, and rules and knowledge. Most often, factors external to the individual (e.g. time pressure and high work load) were identified as the reason for violations, compared to internal factors such as inexperience or lack of motivation. In another study of railway workers, Holmgren (2005) analysed 666 rail accidents and incidents that occurred in Sweden from 1988-2000. He found that the activities of maintenance workers themselves, rather than a lack of maintenance, were responsible for the majority (79%) of maintenance-related events. Of these, rule violations, such as performing track maintenance without permission was the second most frequent contributor to these incidents. Torp and Grøgaard (2009) also examined the workplace climate and situational factors that determine the conditions under which compliance with safety rules will occur. In addition to factors relating to the individual, they found that social support and management support were significant factors in compliance. From the studies quoted above, it appeared that individual and organisational factors combined to motivate individuals to comply with or violate rules. Investigation of the types of violations committed and the circumstances surrounding these violations can be a valuable indicator of what the motivations were, and additionally, what organisational changes are required to reduce the adverse effects of non-compliance.

2.8.5 Additional individual factors

As mentioned above, the commission of violations was thought to be influenced by affective factors, such as motivation and satisfaction. These and many other affective (Brief & Weiss, 2002) and cognitive (Hodgkinson & Healey, 2008) human factors operating at the individual-level have been considered to directly impact on organisational outcomes; and so, they might influence the performance of maintenance tasks as well. *Motivation* and *Job satisfaction*, associated above with rule compliance, might be expected to have the greatest influence on the reliability of maintenance task performance. Martin (2004) considered these two constructs, and the related construct of *Commitment*, to be dimensions of positive and supportive workplaces, and these will be considered here.

Hudson (2007) examined the development of interest in the role of motivation in job performance in the petroleum industry after the Piper Alpha platform explosion. He argued that developing motivation, particularly intrinsic motivation, was required in order to positively affect outcomes in relation to safety. Behaviour could be changed through extrinsic motivation, but long-term changes in behaviour could only be affected by changing underlying beliefs, which needed to be intrinsically motivated. In their experiments, Cassignol-Bertrand, Baldet, Louche, and Papet (2006) found that potential candidates for a position were judged to be more useful to an organisation if they demonstrated intrinsic motivation as opposed to extrinsic motivation. They concluded that intrinsic motivation was a social norm against which employees could be judged. In a review of work motivation theories, Latham and Pinder (2005) highlighted many dimensions of work motivation that impacted on job performance, including job design, self-efficacy, and social skills. For example, a motivationally-oriented job design, in which autonomy of workers was high, was important to performance, but only in less-routine jobs. This type of job design was found to contrast with mechanistically-oriented designs, in which efficiency was of greater importance, confirming that job design needed to be considered in relation to the required outcomes. Furthermore, levels of social skills and self-efficacy (Bandura & Locke, 2003; Choi, Price, & Vinokur, 2003) were mentioned as moderating factors that influenced the relationship between motivation and job performance. Maintenance work consists of both routine and non-routine tasks, as discussed in the section describing *the maintenance task*. The influence of motivation might prove to be a factor in determining the reliability outcomes from maintenance activities, but the nature of job design for the majority of tasks needs to be considered.

Meyer, Becker and Vandenberghe (2004) examined the contribution that commitment makes to motivated behaviour, particularly in relation to *discretionary* activities, not specifically required by the job. They developed an integrative model which drew on various dimensions of commitment that support motivated behaviour, including goal regulation and empowerment. They also discussed commitment as a component of motivation, relating to various social foci of workers, such as their organisation, their work, and their colleagues. However, they concluded that "little attention has been paid to understanding how employee commitment affects behaviour" (p.1004). One study that did examine commitments and outcomes was conducted by Loche and Lanneau (2004). They conducted an 18 month longitudinal trial with two groups of workers (n=26 in each group) to study the short term and long term influence of commitment *(l'engagement*) on safety behaviour. They found that, judging by four factors, developing commitment was more effective than persuasion in modifying attitudes and behaviour in both the short term and long term. The implications for the current study are that a maintenance workforce committed to their roles and supported in their work by the organisation (Muse & Stamper, 2007), is more likely to take responsibility for equipment reliability than a workforce that requires on-going persuasion to do so.

Carr, Schmidt, Ford, and DeShon (2003) further identified links between commitment, job satisfaction, and job performance, through their meta-analysis of 51 studies. They concluded that organisational commitment and job satisfaction mediated the relationship between several dimensions of workplace climate and job performance. Other studies have also demonstrated that job satisfaction was associated with orientation towards successful outcomes (Martin, 2004) and positive task performance (Varca & James-Valutis, 1993). Edwards, Bell, Arthur and Decuir (2008) analysed the influence of job satisfaction on job performance. To determine the role of job satisfaction, task performance was assessed based on supervisors' appraisals of subordinates' work quality. This was supplemented with measures of contextual performance, namely, willingness to participate in the workplace beyond immediate responsibilities. They had expected that job satisfaction would tend to favour task performance, but in addition, they found an equal impact on contextual performance. In another analysis of the factors contributing to job satisfaction Axtell, Wall, Stride, Pepper, et al (2002) found that job satisfaction increased for workers exposed to new technology and work practices. Interestingly, while all employees appeared to respond positively to increased complexity in their jobs, only workers in operational roles demonstrated greater openness to change. Managers and engineers who had greater exposure to change became less open to change with time compared to the low exposure group. The petroleum industry has experienced many technical innovations and so these results may indicate the potential for conflict between professional and non-professional roles as new technology is introduced.

In much of the literature, the errors committed by humans in the workplace are still the most important factor in determining organisational reliability. As a consequence, reducing the performance-shaping factors that provoke the errors made by individuals has been viewed as the major goal of reliability research. However, along with a concern for errors, has been recognition of the impact on outcomes of deliberate violations of task-related procedures. Motivation, commitment, and job satisfaction were viewed in turn as influencing both the compliance with work procedures, as well as having a direct impact on the performance of work tasks. Implicit in these affective factors is the social environment in which individuals perform these tasks. In the next section, research on group-level human factors will be reviewed in order to understand the socio-technical context in which maintenance reliability develops.

2.9 Human Factors in Organisational Reliability at the Group Level

2.9.1 Team function.

One of the group-level dimensions that was often invoked in research as a prerequisite for high-reliability in the petroleum industry was the effective functioning of work teams. Attitudes to teamwork among team members was described as a factor in the effectiveness of 91 offshore oil drilling crew members in reducing errors and incidents (Crichton, 2005). Crichton reported a generally positive attitude among off-shore teams to teamwork, such as 80% of respondents in the survey agreeing that other team members supported them in their work. Despite this, respondents acknowledged that communication, planning, and team stability were still the main problems that they faced. Only 40% thought that team leaders described and explained their plans, and only 35% thought that they were given adequate, timely information. As well as the petroleum industry, studies in health care offer insights into the value of effective team function. In a survey of teamwork in hospitals (Flin, Fletcher, McGeorge, Sutherland, & Patey, 2003) 90% of anaesthetists were found to support the concept of teamwork in medical teams. Despite this overwhelming majority having a supportive attitude and also claiming to enjoy teamwork, they too reported problems in practice with a number of elements of teamwork. Aspects of a properly functioning team include communication, a supportive environment, and mutual error-checking. The study found that only 40% thought that communication (e.g. team briefings) was important for teamwork. Another 35% did not feel that operating staff worked as a team, indicating a less-than-supportive environment for a large part of the team. Finally, only 39% felt that mistakes were handled sufficiently well with the team to prevent recurrences by team members. The implications for the current study of maintenance teams is that care is required in interpreting positive attitudes towards teamwork, as there may be significant shortfalls in the practice of the dimensions of teamwork.

One of the most significant developments in understanding the characteristics needed in petroleum production and maintenance teams to ensure high-reliability, has been in the concept of Crew Resource Management (CRM) (Flin, O'Connor, Mearns, & Gordon, 1999). CRM’s development has advanced furthest in the field of aviation (Salas, Burke, Bowers, & Wilson, 2001). The concepts from aviation have been adapted into CRM training programs for offshore petroleum workers by O'Connor and Flin (2003). Teamwork, leadership, situation awareness, team decision making, communication, and personal limitations were included in their training program. These relate closely to the various dimensions of teamwork in the studies described below, particularly in the requirement to detect and correct errors made by team members. In relation to the value of CRM, Flin et al (1999) quoted a study of 1268 incidents from off-shore production from 1994 to 1996. Almost half (46%) of the human factors-related incidents were found to relate to the items included in CRM training. Other contributors to incidents included lack of skill or knowledge, or poor engineering designs, as discussed in Section 2.7.1.

Another cognitive aspect of effective teamwork mentioned by O'Connor and Flin (2003) was the development among members of shared mental models. Mathieu, Goodwin, Heffner, Salas, and Cannon-Bowers, (2000) considered that sharing an understanding between team members involved more than just a common concept of the required tasks, for example, agreement on which equipment needed to be repaired. They suggested that a shared understanding of normative processes within the team was also required, that is, a common agreement concerning how a maintenance technician accomplishes those tasks. Furthermore, for true team effectiveness, there also needs to be a common recognition of the capabilities and limitations of the team members themselves, such as a lack of critical knowledge within the team (Cooke, Salas, Cannon-Bowers, & Stout, 2000). In their study, Mathieu et al (ibid) tested the influence of sharing both task-based and team-based mental models, and found that both were predictive of the performance of the participants. Based on this, analysis of a maintenance failure should consider whether it was the task performance that was flawed, or team norms that were inadequate to the particular situation.

Konogiannis (1999) contended that another important aspect of teams that promoted reliability was the ability to detect and correct errors committed by members of the team. He explained strategies for how teams could deal with their own errors, with detection and feedback being the critical mechanisms. He then argued that error recovery takes place based on an understanding among other team members of the actions of the error-maker and the outcome that was intended. Therefore to be effective, this basis for detecting errors and communicating observations between team members should be a part of job design and team structuring.

Sasou and Reason (1999) carried the concept of error correction within a team context further by developing a taxonomy for characterising shared team errors as distinct from individual errors. They described the various internal and external PSFs responsible for errors that were considered to be shared among team members. These included *Deficiency in Communication*, *Excessive Belief* (e.g., assumptions), and *Excessive Authority Gradient*. They concluded with the statement, "Many of these problems have their origins in deficiencies of responsibilities" (p.8), which agrees with Hudson's (2007) argument that internal motivation was mainly a function of sense of control. Sasou and Reason's concern with 'vague responsibilities' within the teams they studied, suggested that teams need to be designed around their required tasks. Their concern with team-related errors further reinforces the argument for designing workplace systems around non-technical considerations, as well as around the technology used, as suggested by Bourrier (2005). The design of workplace systems will be considered in Section 2.11.2.

2.9.2 Supervision and leadership.

A group-level dimension that has been frequently studied in relation to organisational outcomes in the petroleum industry is the influence of supervisory practices and leadership styles on work teams. As well as examining teamwork, Crichton (2005) also examined the attitudes to leadership among petroleum drilling teams. He found most drilling team members (83%) preferred a consultative style of leadership, though the style they worked under tended to be more autocratic. Another study demonstrated that to be effective, a change to a group-level approach among managers was required to increase their effectiveness. O'Dea and Flin (2001) examined the attitudes of Offshore Installation Managers in the petroleum industry towards leadership in relation to safety outcomes. Although most managers considered that the elements of a *Consulting/Participative* style of leadership would produce greater improvements to safety performance, 57% preferred a *Directive* leadership style. In keeping with their preferred leadership style, they ranked the causes of accidents as *Not thinking the job through* (#1), *Carelessness* (#2), and *Failure to follow rules* (#3), rather than attributing the causes to problems inherent in their organisation's safety systems or work situations, such as *Inadequate procedures* (#13) or *Lack of resources* (#20). As a consequence, they tended to believe that it was 'not easy' either to *Get workers to accept ownership of safety* (78%) or to *Motivate subordinates to work safely* (60%). In contrast to this view of individual-level interventions, 71% thought that *Promoting an open atmosphere for reporting accidents* would be 'easy', indicating a more positive attitude towards introducing a group-level approach.

The role of leadership in maintenance team performance has been examined in other industries, such as energy generation (Eti, Ogaji, & Probert, 2006) and transport (Hiller, Day, & Vance, 2006). Eti, Ogaji and Probert investigated maintenance management in industry in Nigeria and concluded that wise leadership, communication, and attention to human factors were the most important dimensions of strategies in maintenance processes. Hiller, Day and Vance studied *Collective leadership* in road maintenance teams to determine its effect on group performance. They found that collective leadership was generally associated with higher ratings of most aspects of group performance, with the exception of collective problem-solving. Furthermore, they commented that shared leadership behaviours seemed to be a better predictor of reliable performance than task-sharing behaviours. Research indicating the potential effects of leadership on reliability has also originated from the field of workplace safety. Barling, Loughlin, and Kelloway (2002) studied the links between leadership and outcomes, in this case injury rates. They were able to develop a Structural Equation Model explaining the relationship between transformational leadership style and occupational injuries in restaurant workers. The best fit with their data was obtained with a model in which safety-consciousness and safety climate mediated between leadership and outcomes. Of interest in the current research was the finding of Kozlowski and Doherty (1989) that the perceptions held by more-effective workers aligned with their supervisors' perceptions on a number of scales. These scales included *Work structure, Job understanding,* and *Communication flow,* all of which are important dimensions of a maintenance workplace, and therefore are likely to mediate the relationship between leadership and reliability. As discussed above, reliability and safety have many shared characteristics and may be supported by similar organisational mechanisms.

Wu, Chen and Li (2008) also developed and validated a Structural Equation Model for the linkages between leadership and safety performance, again mediated by climate, among faculty and staff in a university-based study. Their *Safety Performance Scale*, which measured self-reported safety behaviours in an organisation, was used as the dependent variable in assessing the effects of *Safety leadership, Safety performance,* and *Climate*. The relationship between *Leadership behaviours* and *Safety climate* was strong (β=.821) as was the relationship between *Safety climate* and *Safety performance* (β=.701). The direct effect of *Safety* *leadership* on performance was much weaker (β=.179), indicating the importance of considering the influence of climate factors in assessing the impact of supervisors.

One of the moderating factors recognised as playing a role in the effects of leadership on safety behaviours is the form that supervisory practices take. Leadership has been considered an important factor in organisational performance, and specific types of behaviour of the leader were found to moderate outcomes. Kelloway, Mullen and Francis (2006) compared the frequencies with which safety-specific transformational and passive supervisory behaviours were reported in relation to injuries experienced by university students in their workplace. In their study, it was found that the extent of transformational leadership exhibited had increased both safety consciousness and climate, but passive leadership had a significantly negative effect. Safety climate was in turn found to exhibit a negative correlation with safety events and injuries, mediating between the behaviours of leaders and outcomes.

In another study of the effect of leadership style on safety performance, Zohar (2002a) examined the influence of supervisory practices on safety behaviours in 42 manufacturing workgroups. He found that the relationship between leadership, climate, and safety outcomes was dependent on the supervisory style. Although leadership using a transformational or constructive style demonstrated a direct effect on injury rates, the effect of corrective leadership style was mediated by climate and moderated by *Assigned safety priority*, that is, the level of concern for safety communicated by the supervisor's manager. Of the climate variables measured, only *Preventive action*, and not *Reactive action* or *Prioritization*, mediated the effect of leadership on injury rates. He concluded that leadership produced a noticeable effect on safety outcomes, but that the style of supervision and the influence of climate and upper management priorities also needed to be considered. Zohar considered that reliable performance, characterised by a climate of monitoring and rewards, could be developed through a transactional relationship between supervisors and subordinates. However, in dealing with the potential for accidents in non-routine situations, a transformational style provides a better basis for open communication and development of employee decision-making skills. This is relevant to the current research, as much of the maintenance task involves non-routine situations.

Therefore, in addition to the quality of supervision, the style of leadership would be expected to play a role in maintenance group performance.

Zohar and Luria's (2003b; 2005) studies also highlighted the importance of considering cross-level effects (including management priorities, supervisory style, and workgroup climate), arguing that much of the safety research had ignored group-level effects in favour of either individual or organisational factors. In applying this knowledge to interventions in a maintenance centre for heavy-duty equipment, Zohar (2002b) found that weekly communication of safety priorities from managers to supervisors resulted in an improvement in supervisory safety practices, as indicated by the frequency of supervisor/worker interventions, from an initial rate of 9% to a rate of 58%. This, in turn, was accompanied by a decrease in micro-accidents, an increased use of earplugs, and an improvement in safety climate perceptions, which did not occur in the control group. In a similar intervention in an oil-refining company (Zohar & Luria, 2003b), supervisors were given twice-weekly feedback from their managers concerning their safety interactions with sub-ordinates. Over the 12-week intervention, the rate of supervisory interactions increased from 35% to 50%, with a further increase to 70% during the 20-week follow-up phase. At the same time, unsafe behaviours decreased from a rate of 20% to near-zero. This was in contrast to earlier attempts to improve safety which targeted only the individual worker level. This research suggests that efforts to improve maintenance outcomes may be similarly effective if consideration is given to group-level supervisory practices.

2.9.3 Communication.

As Muchinsky (2003) argued in his review of Systems Theory, "the Achilles' heel of most large organisations is failure to communicate… because communication is the means by which the system can be responsive to its environment" (p.250). As suggested above, research into several aspects of petroleum operations have included an examination of communication effectiveness. CRM training in offshore operations specifically included a module devoted to communication (Flin, O'Connor, Mearns & Gordon, 1999). The topics in this module were:

- The advantages and disadvantages of one- and two-way communication
- The importance of feedback

- Internal and external barriers to communication
- Requirements of good communication (p.4)

Crichton (2005) in his survey of off-shore drilling teams, found that nearly all respondents (>90%) agreed that pre-task briefings were essential to teamwork and that social skills were as important as technical skills. Despite this, only ~40% agreed that team leaders communicated and explained procedures and decisions, and ensured that these were understood. Consequently, he commented that "Planning/anticipating events unsurprisingly was considered to be the main challenge to teamwork, followed closely by communication" (p. 679-696) with communication suggested by respondents as the most favoured means of improving teamwork. Similarly, in surveying the perceptions held by Offshore Installation Managers in the petroleum industry, O'Dea and Flin (2001) found that the fourth most commonly suggested cause of accidents was *Lack of communication*. Furthermore, in their opinion Offshore Installation Managers considered that "the non-technical issues, such as leadership, communication and employee motivation, are the issues which now need to receive some attention, as opposed to the technical and design issues which have been the principal concern in the past" (p.51).

Similar developments in Maintenance Resource Management (Taylor, 2000), modelled on CRM, included an emphasis on communication between management and aviation maintenance technicians. Factor analysis highlighted the relationship between communication and effective coordination as well as the important role of pre-assignment briefings and de-briefings for coordinating tasks. As a further example of communication in maintenance activities, Holmgren (2005) investigated the causes of 263 track-related railway derailments and collisions in Sweden. Of the 30% of accidents that could be attributed to maintenance work, the majority had as an underlying cause of poor communication, such as between maintainers and train dispatchers, and a resulting lack of information. In his opinion, not fully utilising maintainers' skills was one of the consequences of poor-quality communication with maintainers. He expected that the use of contractors, particularly with limited experience of a particular workplace, would require even more effective transferring of information in order to mitigate risks.

Information transfer to ensure quality decision-making was also reported to be critical to health care workers. Roberts and Tadmor (2002) analysed the way in which a breakdown of communication between crew members resulted in a naval accident, and then demonstrated how the same process could occur among hospital teams. They explained that this occurred when status and authority gradients take precedence over effective information transfer. Communication across status levels appeared to be the source of medical errors in various studies quoted by Alvarez and Coiera (2006). In one study, the activities of doctors and nurses in an Intensive Care Unit, and the attendant errors, were recorded over a four-month period. Despite doctors communicating verbally with nurses in only 2% of these activities, 37% of the reported errors involved doctor/nurse communications. This may be analogous to communications between engineers and maintenance technicians in industrial environments. It would therefore be instructive to monitor mis-communication between these groups in investigations of petroleum industry failures.

Information transfer between hospital teams during patient handovers was also found by Horwitz et al (2009) to be critical. In a survey of 139 emergency department physicians and internists, they concluded that "Communication failure was implicated in most errors [relating to handovers from the emergency department] and included failures of message and failures of interpersonal relations" (p.707). Much of the difficulty involved lack of communication across discipline boundaries, as well as differences in understanding between people working in different disciplines. A similar effect would be expected in communications between off-shore maintenance technicians and on-shore engineers in the petroleum industry, who also are required to communicate across discipline boundaries. A solution that Horwitz et al proposed for 'message-related problems' is to standardise the information content of messages. For example, the design of message checklists could be specified in order to set a benchmark for the minimum information levels required. This is a concept that could be operationalised in petroleum maintenance activities, in which work orders derived from computerised maintenance management systems (CMMS) are generated for most maintenance activities.

In addition to the quality and content of communication, the medium used has also been identified as a factor affecting the reliable transfer of information. Considerable interest has developed regarding the efficacy of contemporary communication media, particularly in comparing synchronous to asynchronous media (Baker, 2002), and computer-based to face-to-face communication (Baltes, Dickson, Sherman, Bauer, & LaGanke, 2002). Baltes et al in their meta-analysis of group decision-making found significant effects on work outcomes, time-to-decision, and member satisfaction associated with computer-based communication compared to face-to-face meetings. No significant effects were found relating to group size or type of task, but groups communicating by computer performed more poorly on problem-solving and negotiation type tasks. Furthermore, the effectiveness of computer-based communication was not significantly different to face-to-face groups when the members were anonymous and had no time limits on making decisions. However, as the authors explain, these do not constitute the usual situation in organisations.

In a study of the way that members of an armoured brigade communicated, Zohar and Luria (2003a) found that the format of communicating messages was also associated with communication effectiveness. Specific within-group dialogue formats, which they called ‘meta-scripts’, were used to manage both the complexity of operational situations, as well as the variety of actions required. As the complexity that a situation required increased, so did the script complexity. The use of 15 meta-scripts, which were particularly meaningful to the members of the units in the study, was found to be the basis for the efficient transmission of critical information needed to coordinate activities. This form of communication allowed the generation of shared mental images in a short timeframe and with a parsimonious use of language. Zohar and Luria found that, as well as a basis for decisions and actions, meta-scripts also accommodated organisational learning, as new understandings could be rapidly adopted through modification of existing scripts. This compliments the findings of Tucker, Edmondson, and Spear (2002) concerning the problems encountered by nurses. The absence of an efficient format for communication meant that second-order problem-solving, required for organisational learning, did not occur. Nurses did not have sufficient time available to them to compensate for the prevailing inefficient modes of communication.

A central aspect of maintenance group performance is inter-group and intra-group communication, as all maintenance activities require some form of interchange between the various participants. The need for efficient formats of communication in the petroleum industry may prove particularly relevant to the current study in which maintenance teams, engineering and vendor support, and management were distributed across a distance of over 2000 km with limited opportunity for face-to-face exchange of information.

2.9.4 Decision-making.

Another process considered by researchers to be central to the function of workgroups is decision-making (Wright, 1974), particularly under organisational pressures. Researchers have been investigating the decision-making process for some time, both at the individual level (Janis & Mann, 1977) and at the group level (Kerr & Tindale, 2004). Decision-making is a critical dimension of reliability through its mediating role between the workplace inputs, essentially task demands, and the required workplace output (Oedewald and Reiman, 2002). Several aspects of the literature on decision-making are particularly relevant to the current study of maintenance work groups. Ajzen's (1991) Theory of Planned Behaviour, which in turn was based on the Theory of Reasoned Action, would appear to be consistent with decision-making in a workplace in which repair of advanced technical equipment is involved. The Theory of Planned Behaviour would explain that maintenance decision-making consists of rational consideration of repair alternatives, followed by selection of suitable actions in accordance with group and organisational norms. Contrasting this, later research suggested that the decision-making process in an industrial environment follows a less-predictable cognitive process. Rasmussen and Jensen (1974) investigated the cognitive process used by maintenance technicians responsible for repairing electronic equipment. They identified that only 20% of trouble-shooting processes were based on 'careful reasoning' related to a mental model of the faulty system, while 70% were based on faster, experience-based recognition of the fault. Carvalho, dos Santos and Vidal (2005) found a similar ratio when they examined the decision-making process among shift supervisors in a Brazilian NPP. They observed that 80% of decisions were made with a 'pattern recognition process', and only 20% through a decision-making process that was similar to that described by the Theory of Planned Behaviour. Carvalho et al concluded that most of the processes they had observed were consistent with the pattern recognition process termed Recognition-Primed Decision-

Making by Lipshitz, Klein, Orasanu, and Salas (2001), in which decisions are made on past experience. Past experiences generate internal *Condition/action rules*, which then take precedence over the organisation's operating procedures. In Recognition-Primed Decision-Making, the first option encountered that fulfils the requirement criteria with a sufficient probability of success would be accepted by the decision-maker, generally without consideration of further options. Lipshitz et al argued that, "If a moderately experienced person can generate a workable solution as the first one considered, there may be reduced incentives and benefits from generating and evaluating additional courses of actions" (p.337). However, on this basis, assumptions can enter into the decision-making process at an early stage in order to compensate for a lack of complete information, and the need to arrive at a sufficiently-acceptable solution under time pressures. This may be typical of a related concept, Naturalistic Decision-Making (Klein, 1997), which is more likely to occur within complex environments with multiple objectives and time pressures, and where information is limited and procedures are at times poorly-defined.

Interestingly, Carvalho et al (2005) reported that the decisions of shift supervisors were "biased by underlying assumptions" (p.642) that were different to those of the control room operators. These differences in biases could be explained by the existence of shared and unshared information among group members, described as the concept of *Hidden profiles* by Stasser and Stewart (1992). Hidden profiles are related to the concept of shared mental models, described above in Section 2.9.1 on *Team Function*. Stasser and Stewart observed that knowledge of experienced group members was not always shared with other group members, if seemingly enough shared information was available to the group. When this occurred, the group's objective was consensus rather than making the correct decision, in a process they term 'judgement vs. problem-solving'. Consensus required only a mutually acceptable judgement, but a correct solution was seen to require problem-solving. In their experiments, they found that unshared information only became more critical to the group when there was a perception that a correct solution existed. However, they described how, in another study, personal accountability was found to influence the acceptance of shared compared to unshared information. These findings have implications for decision-making within maintenance groups in terms of the need to encourage information sharing, foster a perception of accountability, and recognise the importance of genuine problem-solving over judgements.

2.9.5 Problem-solving behaviours

As described in Section 2.2 on *The Maintenance Task*, corrective maintenance work requires problem-solving to restore equipment to fully operating condition. Reliability in corrective maintenance depends on achieving a correct diagnosis and applying an effective solution when dealing with faulty equipment. Schaafstal, Schraagen, and van Berlo (2000) investigated problem-solving behaviour among maintenance technicians in the Dutch navy. They observed a tendency of technicians to use *Case-Based Reasoning* rather than a structured approach in trouble-shooting equipment. In effect, they attempted to relate problems to previously encountered problems, a process similar to Recognition-Primed Decision-Making described above. They regarded novice maintenance technicians as particularly lacking a functional understanding and consequently not developing a logical strategy for 'reducing the problem space'. They argued that in order to improve the performance of maintenance technicians, training should have a greater focus on ways of developing trouble-shooting strategies, and less on acquiring system knowledge. Although many of the same considerations may apply, maintenance in major petroleum facilities poses additional challenges compared to the repair of individual items of equipment. Hokstad, Øien, and Reinertsen (1998) considered that for offshore petroleum facilities, for which the high level of reliability often meant that little failure data was available, expert judgements could be integrated with operational data to solve existing and potential reliability problems. They considered that experts could support decision-making through structured judgements better than engineering analyses could. This demonstrated the value of an innate understanding of the processes involved compared to a solely technical analysis of data.

Dorner (1987) also studied problem-solving behaviours in complex, non-transparent, dynamic environments, and described the flaws in cognitive processes that he observed. He developed a simulated problem-solving experiment, constructed around deliberately complex decisions on the part of the participants. The experiment involved the participants making decisions concerning the running of a fictional European town represented in a computer model. The flawed problem-solving processes that he identified included:

- focus on the status quo and an inability to observe trends
- linear thinking instead of visualising the causal nets which link aspects of the problem
- 'thematic vagabonding' in which the subjects considered a topic, but only superficially, before moving onto another topic
- tendency to accept confirmatory information while ignoring contradicting information
- tendency to form hypotheses around global concepts rather than around specific observations.

Dorner considered that these flaws in problem-solving processes identified in his experiments would also occur in real-life situations, and that in an emergency situation these tendencies would become even more pronounced. As much of the maintenance task involves finding solutions to failed or poorly-operating equipment, there is a danger that these tendencies will influence the cognitive processes of maintenance technicians. Furthermore, the greater the pressure to complete repairs in order to restore production quickly, the more likely flawed problem-solving is to occur. As the current research is concerned with past failures, it will be instructive to determine if these impediments to problem-solving are a contributing cause.

In an empirical study of problem-solving in American hospitals, Tucker, Edmondson, and Spear (2002) observed that nurses successfully solved immediate or first order problems, a process colloquially known as 'fire-fighting'. However, without second-order problem-solving, that is, genuine elimination of the underlying causes of problems, the same failures would generally reoccur. This was attributed to a lack of methods for resolving problems, as well being a function of the organisational climate. The climate observed was typically characterised by inadequate mechanisms for communicating problems and a shortage of resources, such as time. Tucker, Edmondson and Spear found that only 8% of problems were genuinely resolved by nurses and that these "efforts were often opportunistic, weak and unrecognised as a request for organisational improvement" (p.130). They argued that changing this required a workplace that provided opportunities for feedback from workers to management, and that encouraged “workers’ motivation to engage in longer-term improvement efforts” (p.135). Tucker et al. considered that these issues applied to ‘frontline workers’ in general, and many of their situational descriptions could easily be applied to maintenance technicians in the petroleum industry. For example, they discussed situations in which doctors ignored nurses’ recommendations concerning patient treatment because of the lower status that nurses had in relation to doctors. For a similar reason, Cooke (2002) found maintenance technicians often expressed the feeling that their ideas about improving equipment repair procedures were not heeded by engineers. Allowing technicians to up-date procedures based on problem-solving experience is an important element of organisational learning, which will be discussed in Section 2.10.3.

The development of a problem-solving culture was further explored by MacDuffie (1997). He examined the way that functional problem-*resolving* embedded within organisational processes provided workers with the means to eliminate the underlying causes of failures. In his analysis, he compared the problem-solving processes within work teams at three automobile manufacturing plants in the United States (i.e. Ford, General Motors, and Honda). Each of the three plants studied exhibited a different organisational approach to problem-definition, problem-analysis, and solution-generation behaviours within the workforce. The most effective problem-solving processes were identified within the Honda plant, where problems and small failures were viewed as an opportunity to learn, to adapt, and to prevent more expensive systemic failures. Particular heuristics that were embedded in the organisation assisted in creating a problem-solving culture. One such heuristic was called ‘actual part, actual situation’. In this approach, the person solving the problem was encouraged to observe the situation first hand in order to “analyze it systemically, to communicate the problem more accurately to others in his/her team, and to be motivated to find a preventive remedy” (p.492). Other organisational approaches to problem-solving described by MacDuffie included:

- The formation of problem-solving teams based on ability to contribute to the resolution of the problem, that is that problems belong to the entire company.
- Elimination of status barriers between groups and individuals, as the solution of problems in other companies were often inhibited by these barriers.

- Acceptance of changes and the possibility of resulting failures, as in the quote attributed to Soichiro Honda, the founder of Honda, “It’s OK to fail 99 times, as long as you succeed on the 100^{th} time” (p.499). This is complemented by a standardisation process for precisely assimilating successful developments into work processes.

MacDuffie concluded by acknowledging the importance of “the development of a common language for discussing problems” (p.501), and acquiring the information needed to develop a range of perspectives on a problem.

The studies on problem-solving demonstrated that an effective problem-solving climate needed to be based on the institution of methodologies and heuristics within the organisation. Proctor and van Zandt (1994) explained that many methodologies and heuristics had been developed to aid problem-solving; but cautioned that many common fallacies in logic had lead people to the wrong conclusions. They contended that these fallacies in logic often occurred because required information was presented in a complicated format, or because of the way that problems were framed. In the complex environment of petroleum operations, the use of decision-support methodologies and training in problem-solving have the potential to improve the mental representations of maintenance problems and hence reduce the potential for errors of logic to occur.

2.10 Human Factors in Organisational Reliability at the Organisational Level

Although, the preceding section has focussed on the factors that are principally manifested at the group-level, namely team work, communication, decision-making and problem-solving, the literature has demonstrated that these processes are associated with processes at the organisation level. Organisations have a significant role to play in terms of facilitating group processes and assisting maintenance groups to perform their tasks successfully. The following is a review of organisational-level processes that may contribute to reliability through their impact on maintenance groups.

2.10.1 Organisational climate.

At the organisational level, much of recent research has been concerned with what has come to be called *Organisational climate*. Parker, Baltes, Young, Huff, Altmann, Lacost, and Roberts (2003) considered climate to be a "property of the organisation itself and represents employees' descriptions of an area of strategic focus or organizational functioning" (p. 391). They distinguished organisational climate from other climates, such as psychological climate, which represents an individual level dimension, and from particular climates, which relate to specifics aspects of the workplace, such as safety climate (Cox & Cheyne, 2000; Mearns, Whitaker, & Flin, 2003; Sorensen, 2002; Zohar, 2008). Zohar and Luria (2005) considered climates to manifest at all organisational levels, existing as "level-adjusted perceptions or appraisals of relevant policies, procedures, and practices as indicators of desired role behaviour" (p.616). In contrast to the focus of organisational *climate* on employees' perceptions, Schein (1996) viewed organisational *culture* as being concerned with a "set of basic assumptions about how the world is and ought to be" (p.11). Schein further explained that "perceptions, thoughts, feelings and to some degree their overt behavior" (p.11), result from these shared assumptions. In relation to maintenance technicians, culture relates to shared beliefs about how the company expects maintenance to be executed, while climate describes the experience of trying to conduct maintenance activities in a particular workplace.

Research in the area of off-shore safety climate was useful as a means of understanding the way that organisational climate has the potential to affect reliability in petroleum operations. As discussed earlier, safety and reliability were frequently associated in the literature, particularly when the term safety was used to refer to reliable operation of hazardous technology. Case studies by Hokstad, Oien and Reinertsen's (1998) indicated that the concept of reliability in organisational processes has more in common with developments in process safety climate than it has with engineering design principles, with which it is usually associated conceptually (Lewis, 1996). Further, in common with workplace safety, the climate experienced by maintenance technicians in a complex socio-technical system emerges from the continuous interactions between humans and complex, potentially dangerous, machines. In his early work, Zohar (1980) was one of the first to formulate a connection between the safety of workers in industry and their performance in relation to reliable maintenance work. His idea was that, "When all these organizational characteristics are integrated, it is possible to form a coherent organizational pattern of a highly safe company…This climate results in increased performance reliability of workers, good housekeeping, and high design and maintenance standards" (p.97).

Extrapolating from this connection between safety climate and reliability, the climate factors that influence safe behaviours therefore are logical candidates as the dimensions of reliable maintenance work. Mearns, Whitikaer, and Flin (2003) measured the dimensions of safety climate that contributed to safety performance in 13 offshore installations. They found that communication and decision-making variables were significantly correlated with accident rates, both factors identified above in the literature on reliability. They attributed the importance of these two factors to their role in organisational learning, discussed below in Section 2.10.3. Flin, Mearns, O'Connor, and Bryden (2000) examined the changes in measures used to determine safety climate in the energy industry. They found that organisational measures related to risk, competence, and perceptions of management attitude were more commonly used in the 18 methods that they examined rather than injury rates. The effects of risk, competence, and management processes on climate variables would be applicable to reliability studies, though data on injury rates would not. In reviewing studies on climate and safety (Geller & Douglas, 2005; Glendon & Litherland, 2001; Torp & Grøgaard, 2009), a number of factors contributing to organisational climate, such as job demands, decision authority and social support were implicated as influencing outcomes, notably the reported injury rates. Furthermore, Zohar (2008) discusses dimensions of organisational climate beyond safety climate, suggesting that work-ownership climate also impacts independently on safety-behaviour. His description of work-ownership as including commitment to the work and "a proactive orientation characteristic of stewardship and citizenship behaviour" (p.382) could underpin good practice in maintenance as well as safety, as it mirrors the concepts of monitoring, anticipating, and reacting in Oedewald and Reiman's (2003) maintenance core task model discussed later in Section 2.11.2. In Zohar and Luria's (2005) study of production workers in small and medium sized manufacturing, they further explored the effects of organisational safety climate in the workplace. They found that group safety climate mediates between organisational safety climate and role behaviour, with the effect moderated by the actions of supervisors. The amount of discretion supervisors had was in turn negatively related to the level of routine in the workplace. The implications are that while climate in maintenance groups should be closely related to organisational goals, supervisors will have an important influence on how these goals are understood, particularly where maintenance activities tend to be less routine in nature, as in complex off-shore facilities.

Although it is reasonable to postulate that there are climate factors that will influence all workplace behaviours, studies have indicated that differences may exist between the specific factors responsible for personal safety outcomes and those responsible for maintenance reliability. Most importantly, attitudes and motivation towards risk-taking may be different (Glendon, Clarke, & McKenna, 2006), depending on whether these are technical risks, or health and safety risks. Glendon, Clarke, and McKenna characterised technical risks as engineering assessments of the probability and magnitude of failure, along with considerations of the benefits to be gained by taking a given risk. Maintenance departments assess the risk of deferring maintenance tasks on this basis (Moubray, 1997; Krishnasamy, Khan, & Haddara, 2005) and even the maintenance technicians themselves make these judgements informally, particularly when time constraints and difficult tasks are involved (Mason, 1990). On the other hand, Glendon et al contended that the developed countries have become risk-averse with regard to health and safety, despite the relative safety of contemporary society. The result is that the organisational climate may be characterised by a different level of risk with regard to safety compared to that of reliability. Therefore, although safety research may provide useful clues as to how climate influences outcomes, the role of climate factors must be considered specifically in relation to petroleum maintenance activities.

2.10.2 Maintenance reliability climate.

In an approach based on safety climate research, Reiman and Oedewald (2004) investigated the role of workplace climate in NPP maintenance operations. They developed their CULTURE survey and tested its validity and reliability as an instrument for revealing the differences in perceptions of climate among maintenance workers. The CULTURE scales are based on established climate markers, such as effective communication, control over one's work, and the meaningfulness of work as measurable organisational phenomena. The survey results were expected to reveal intrinsic differences in maintenance approaches between companies, which could be related to differences in attitudes and observable performance among maintenance workers. Reiman and Oedewald anticipated that these latent climate factors would moderate the relationship between underlying personal and team dimensions, and objective measures of task effectiveness.

Reiman, Oedewald, and Rollenhagen, (2005) then applied the CULTURE questionnaire in a study of two Scandinavian NPPs to examine the relationship between climate factors in maintenance workplaces and workgroup efficiency and performance. In one of the NPPs they surveyed, the workers reported that learning and problem-solving were critical to their concept of safety and reliability. In the other NPP, their survey highlighted adherence to procedures and pre-existing knowledge as the perceived basis of reliability. They concluded that ultimately several psychological factors needed to be considered in workplace design within an organisation, irrespective of the specific cultural orientation of the work teams. These factors were communication quality, job control, the meaningfulness of the job, and the structuring of well-defined goals, tasks, and responsibilities. In their discussion of communication climate, they concluded that as an organisation became more complex, for example organised along a matrix structure, structuring communication became both more difficult and more critical to effective functioning.

In further studies, Reiman and Oedewald (2005) also investigated the effects of organisational change on safety and reliability. They found that during a period of workplace re-structuring, the psychological factors that were deemed necessary for the reliable performance of maintenance work, including *Goal clarity, Meaningfulness of work,* and *Sense of responsibility*, had changed in the responses from workers. Their concern was that organisational change could affect both workplace structure and organisation-wide perceptions of these dimensions. They argued that although structural change was generally planned, the changes in organisational processes that ultimately affected perceptions of organisational climate were more likely to occur through “migration or drift in practices and assumptions” (p.5). In their opinion, drift in practices to accommodate a new structure was not necessarily a negative process, but takes time and can detract from performance. Impacts on the workplace climate brought about by management decisions (e.g. clarity of responsibilities, communication structure, and sense of control) needed to be considered when structural changes were introduced into a complex workplace in order to avoid unintended outcomes, such as decreased reliability.

2.10.3 Organisational learning.

As discussed above, problem-solving is a critical process in the maintenance task, part of which involves the organisation acquiring knowledge gained from solutions, through a process known as *Organisational learning* (Lipshitz, 2007). Carroll (1998) examined organisational learning in a chemical process plant and evaluated the logic behind the need to learn from past problems. Analysing recurrent problems through a Root Cause Analysis program provided a mechanism for learning from pre-cursors and near-misses, rather than trial-and-error. He argued that in high-hazard industries organisational learning would be able to provide the resilience and ability to anticipate that was required to avoid 'cyclical crises'. An important aspect of maintenance reliability in the petroleum industry is whether maintenance technicians, having resolved a particular task-related problem, can then translate that into new knowledge within the organisation to prevent reoccurrences of similar problems at other times and in other situations.

The connection between problem-solving and organisational learning has been explored in depth in the US medical industry by Tucker and Edmondson (2003) based on earlier work by Edmondson (1996; 1999). In observations conducted within hospitals, it was found that resolving problems that impeded the accomplishment of critical tasks rarely resulted in acquiring the knowledge needed to prevent reoccurrences (Tucker & Edmondson, 2003). Tucker and Edmondson attributed this lack of learning to three seemingly positive dimensions: *Individual vigilance, Efficiency,* and *Empowerment*. Individual vigilance led nurses to take responsibility for resolving problems, without consideration of the flaws in organisational systems, or feedback to correct these systems. Similarly, empowerment meant that nurses were expected to work autonomously without adequate access to, or support from, management. Finally, the almost universal drive for efficiency meant that once a problem was resolved, nurses could not devote further time to feeding back learnings to others in the hospital system. The 'workarounds' observed were employed to resolve task impediments, but in effect prevented the systematic learning needed to remove the root causes of systemic failures. All of these factors that inhibit organisational learning have analogues within petroleum maintenance teams. As in the medical industry, the drive for efficiency might be the main reason for failure to devote the time needed to learn from past failures and resolve what are considered root causes.

For Edmondson (1996; 1999) the concept of learning behaviour is central to avoiding the types of error that compromise reliable task performance for nurses. In her study of eight hospital teams, she measured the relationship between workplace climate factors and error frequencies. Behavioural observations and a survey provided the independent variables, while the number of *Adverse Drug Events* was the dependant variable. From the results, she concluded that better workgroup processes contributed to higher levels of reporting and discussion of Adverse Drug Events. This then led to the *Second-order learning* described by Argyris and Schon (1996). In their experience, organisations typically devote time and resource to resolving their immediate problems (first-order learning), but do not carry this to the next stage by applying the knowledge gained to prevent recurrences. One reason for the lack of analysis that could lead to second-order learning is that organisations prefer to learn from their successes, rather than their failures (Baumard & Starbuck, 2005). In their case studies of organisational failures, Baumard and Starbuck found that small failures, particularly ones that challenged core beliefs, either were discounted by managers, or were attributed directly to the person responsible for the failed venture or experiment. Large failures were likely to be attributed to outside factors or people outside the company. They concluded that by failing to interpret correctly the underlying contributors to both small and large failures, the potential to avoid future failures was lost.

The recognition of both the importance and the difficulty of promoting learning across organisations, has led to the development of many strategies for organisational learning. This includes strategies for both encouraging learning by individuals within organisations (Gherardi, Nicolini, & Odella, 1998) as well as developing the processes by which organisations as a whole can learn (Lipshitz, 2007). The organisational learning process, formalised by the US Department of Energy in their

Lessons Learned Program (Carnes & Breslau, 2002) was considered to be critical to the development of proper procedural documentation and training within NPPs. Similarly, LearnSafe (Jones & Cox, 2003), a project funded by the European Union, has among its concerns, the “ageing of personnel and preservation of competence” (p.12). As a result of recognition of the value of organisational learning, a common aim of many of these programs was to develop instruments for measuring organisational learning in NPPs (Wahlstrom, Wilpert, Cox, Sola, & Rollenhagen, 2002).

A generic instrument to measure organisational learning is the Dimensions of the Learning Organisation Questionnaire (DLOQ) developed by Marsick and Watkins (2003). It was subsequently tested for construct validity and reliability by Yang, Watkins, and Marsick (2004) in a sample of 836 participants from various service and industrial companies. The DLOQ has been used to measure employee perceptions of learning within an Australian auto parts manufacturer (Dymock & McCarthy, 2006). In that study, the DLOQ was used as part of a program to develop workplace learning among the workforce in order to improve company performance. As a result, some employees saw the approach as empowering, for example, with regard to decision-making in their roles. Others were more sceptical about the company’s motives. To operationalise a learning environment required organisational change and socialising of group members to encourage participation. Lipshitz (2007) studied this process of socialising pilots into what he termed a ‘debriefing culture’. He found that such a culture existed in the form of post-flight reviews in his studies of an air force unit. In this environment, the pressures to avoid making errors were high. Despite this, he observed that errors were admitted during the thorough peer analysis of the post-flight review process. He noted that there was sufficient psychological safety, a dimension described by Edmondson (1999), to ensure that participants felt that they could admit to errors, thereby allowing organisational learning to take place.

Among maintenance teams there are a number of reasons why this may not occur (Reason & Hobbs, 2003) including a “natural disinclination to confess one’s blunders” p.151), as well as concerns about being named in a failure report, and a perception that nothing will be done to rectify the causes. If the organisation does not promote a 'reporting culture', the process of identifying errors before they cause a failure will likely not involve the maintenance technicians themselves. The literature then suggests that organisational learning, and consistent feedback to maintenance technicians, is unlikely to occur (Edmondson, 1996; Tucker & Edmondson, 2003). The probable result is one of experiencing the same failures repeatedly, due to what Cannon and Edmondson (2005) describe as, "both technical and social barriers to organizational learning from failure" (p 300), and particularly the situations in which "when failures are identified, social factors inhibit the constructive discussion and analysis through which shared learning occurs" (p 303). In the following section, the issue of identifying failures in relation to the human factors discussed above will be examined more closely. Of particular interest is the investigation of failures in order to understand the organisational processes operating in the workplace that contribute to the occurrence of failures.

2.11 The Impact of Human Factors on Reliability

2.11.1 Models of organisational failure and reliability

Although many of the earlier studies in human factors cited above had focussed on the role of the individual worker, later research recognised the implications of individuals operating in an organisational context. In groundbreaking work, Rasmussen et al. (1981) considered that the flaws in group-level exchanges and organisation-level processes were 'performance-shaping factors' which could be considered the most fundamental root causes of accidents and failures. This represented a shift in the conceptual framework regarding failure mechanisms involving humans; that is, from one in which humans fail the system (Cacciabue, 2000; Gertman et al., 2002; Vanderhaegen, 1999), to one in which organisational processes are flawed and humans provide the final barrier against systemic failures (Edmondson, 1996). So too have the models relating to reliability changed, from ones primarily concerned with individual-level phenomena (e.g. errors and violations) to those which also consider group- and organisation-level processes (e.g. communication, supervision, and climate). Thus Reason's (1997) Defences-in-Depth or 'Swiss Cheese' model is widely accepted by failure investigators as able to represent flaws which can occur at different organisational levels and within a variety of processes. In the model, a failure or accident can only occur when all the organisational barriers that are designed to safeguard a system have flaws ('holes' in the ‘Swiss Cheese’) or have been breached, allowing a failure sequence to proceed. Reason used this approach to examine the long history of maintenance failures and organisational accidents as part of his discussion of strategies for managing organisational accidents. He described several of the more infamous fatal industrial accidents in which maintenance practices were an identifiable contributor. These included the Flixborough cyclohexane plant explosion (28 killed), the Bhopal methyl isocyanate plant leak (2500 killed), and the Phillip 66 polyethylene plant explosion (23 killed). Reason then proceeded to review the endemic organisational behaviours that contributed to maintenance failures. These included incorrect installations, omissions of necessary steps in a task, deliberate violations of procedures, and flawed decision-making by management.

In a parallel conceptualisation of organisational failure, Rasmussen (1997a) developed a model of “migration towards a boundary of functionally acceptable performance” (p.190) based on his theoretical framework of systemic failures (Rasmussen, 1990). Rasmussen objected to the Defences-In-Depth model of failure, believing instead that as work systems adapted to their environment, ‘catastrophic system behaviour’ could still occur if local activities were not controlled in relation to absolute rather than relative boundaries of safe action. Drift of entire systems under organisational pressures was more of a concern than the appearance of localised flaws in processes, activities, and barriers. He argued that in fact, it was the organisation’s views of itself as coping *relatively* successfully with the dangers that often allowed perceived safety margins to drift closer to real boundaries of safe behaviour.

The concept of drift in safety margins was later expanded by Hollnagel (2002) in his discussion of Systemic Accident Models and by Dekker (2005) in his discussion of Drift Into Failure. Hollnagel first reviewed features of the Defences-in-Depth model, which he refers to as an ‘epidemiological model’, and considered it as problematic in terms of his views on accidents in organisational systems. Dekker (2006) also argued against an epidemiological model, preferring a systemic model. In his opinion:

- An epidemiological model, to be useful, relies on identifying 'latent pathogens', when in reality virtually every facet of an organisation could be the source of these pathogens.
- In addition to latent pathogens, this type of model also focuses on 'active errors', typically inferred to be failings in human performance (e.g. *unsafe* acts, *poor* designs, or *bad* management decisions). In reality, these so-called active errors are typically normal work activities.
- Even epidemiological models tend to reduce accidents to a sequence of events, which is overly linear and too narrowly focussed too provide an understanding of the contributors. Failures are defined by their 'causes', which tend to be difficult to prove and prevent other factors from being considered.

Dekker (2005) then explored various concepts of failure in relation to systems thinking as a way of modelling the type of accidents in socio-technical systems caused by *normal* departures from acceptable practice. As an alternative to the epidemiological model, Dekker expanded on the role of humans in a systemic model recognising that:

- The actions of workers and supervisors prior to a failure typically appear normal to them and could only be understood within the context existing at the time. In that sense, Dekker's concept of these failures aligned with Perrow's (1994) concept of 'systems accidents' described in his Normal Accident Theory. Perrow's Normal Accident Theory attributed these failures in modern industrial organisations to a combination of the complexity of interacting systems with their tight-coupling. With tight-coupling, incipient failures propagated both more quickly and with less opportunity to intervene, presenting a serious threat to high-risk technologies. All this occurs in what appeared to be *normally* functioning systems. Here, the 'drift into failure' is characterised by an acceptance of the status quo as both normal and relatively safe, especially by managers for whom there are political considerations involved in acknowledging safety risks.
- Failures represent a loss of control over safety constraints. The level of control required can gradually change over time. This may be as basic as the loss of experience in a workforce due to high turnover of staff. When loss of control

> extends over multiple interacting factors, which singly could not cause a failure, the probability of failure has been found to increase greatly (Antonovsky, 2006).

Hollnagel (2002) contributed to the development of the concept of a Systemic Accident Model by arguing for assessments of risk to be based on the way that complex interactive systems function, and not on the probability that humans will make errors. In fact, even assigning the label *incorrect action* is only possible once the outcome is known. He contended that humans are involved "at all levels, from the initial design to repair and maintenance" (p.1:3), but that this cannot be invoked as the cause of an accident. Instead, he argued that "variability-rather than human failures-is the central issue" (p. 1:5) in accidents. Hollnagel (2006) also considered that with control came the ability to remove 'unwanted variability' in a system, and at the same time prevent unexpected, and presumably unwanted, events. Hollnagel's model invokes what Dekker (2006) calls the Local Rationality Principle; that is, a working assumption that people will make the best decisions that they can, given the interacting, and at times conflicting, objectives of the organisation, and a complex workplace context.

In any analysis of human behaviour, a framework or frame of reference is needed to make sense of the motivations and activities of individuals in a specific context (Hollnagel, 2002). As Einstein (1926) observed, "Whether you can observe a thing or not depends on the theory which you use. It is the theory which decides what can be observed." In the case of judging the origins of failures and their causal mechanisms, the conclusions drawn will depend on who assigns causes, and what constitutes their frame of reference (Hughes, 1951). These pioneers in the field of human factors, namely Rasmussen, Reason, Dekker, and Hollnagel, strove to develop frameworks in which human activity was intimately connected to the systems in which the work is done. The systems not only determined the positive outcomes of work, but also the negative results in the form of workplace failures. They considered that further research and analysis of the role of human factors in reliability should be aimed at not just examining performance and outcomes. Research was also required to investigate systems at the workgroup and organisational levels, where 'interactive complexity' and an incomplete understanding of the tight couplings in the workplace, were most likely to cause failures.

Such a framework, drawn from studies of humans interacting with advanced technology control systems, was developed in the early writings of Rasmussen and his associates (Rasmussen, 1982; Rasmussen et al., 1981) on human malfunction. In his Human Malfunction model, consideration was given to the various accepted mechanisms of human and systemic dysfunction, internal behaviour drivers, performance shaping factors, and situational factors discussed above. Thus, one aspect of this malfunction was the 'misfit' between workers and machines, or between workers and tasks. Rasmussen's framework recognised the impact of the internal cognitive elements of human malfunction, such as acquiring information, assessing situations, and deciding how to proceed. It also included all of the elements of the external work environment that shaped the way that humans perform. Finally, his framework provided a basis for assessing the observable characteristics of malfunction, such as omissions of tasks, inaccurate performance, or commission of an error. Altogether, the model succeeded in incorporating many of the dimensions that were reviewed in the human factors literature in this chapter as influences on organisational behaviour and performance, including decision-making, communication, tasks not performed, and equipment design. This framework provided a starting point for making sense of how workplace design and the humans in the workplace ultimately influenced the reliability of technical systems. Based on this framework, there appeared to be a need to design workplaces and work systems so that they supported the required work processes and outcomes. In the following sections, these issues are explored in considering the role of workplace design in managing the risks of maintenance failures, which then leads to consideration of the workplace design features inherent in the concept of a High Reliability Organisation (HRO).

2.11.2 The role of workplace design.

Much of the current understanding of the role of maintenance workplace design is derived from research in NPPs. From her research on NPP maintenance, Bourrier (2005) concluded that, in addition to addressing the human factors in technological organisations to achieve the best outcomes, organisations needed to be designed from the start in tandem with the technology employed. Otherwise, there existed the danger that existing systemic failure mechanisms would remain present to cause the normal accidents or systems accidents described above. In addition, the greatest gains in reliability were to be achieved through considerations of organisational design rather than technical improvements. These design considerations included the "coordination of workers and structuring of tasks" (Bourrier, 1996 p.104), as well as formally recognising the need to modify procedures appropriately. Therefore, processes for assessing and correcting the design of a maintenance workplace would be required in any credible reliability improvement strategy.

Reiman and Oedewald (2006a) considered that before a workplace design was assessed to determine if it could fulfil its required functions, a coherent concept of those functions was required. Oedewald and Reiman (2002) conceived of these functions in maintenance work as the 'organisational core task'. They postulated that a clear conception of the organisational core task might be more important to achieving desired maintenance outcomes than enforcing specific practices and procedures. The maintenance core task for them entailed a number of job demands, which they incorporated into the Core Task Model (Oedewald & Reiman, 2003). These job demands were comprised of *critical demands* (i.e. monitoring, anticipating, and reacting) and *instrumental demands* (i.e., methodicalness, flexibility, and learning). In addition there were the *working demands*, such as adhering to procedures, coordination, and defining responsibilities. These constructs were similar to the ones that Bourrier (1996) used to assess the successful operation of two American NPPs. Her assessments of their performance were based on comparing the differing strategies in the two NPPs for handling the demands of maintenance. The measure used to judge successful performance was a qualitative assessment of the relative success of these plants in handling four core elements of the maintenance shutdown process:

- coordinating Maintenance and Operations Departments
- complying with procedures
- adapting to unexpected situations
- controlling the quality of maintenance work.

Bourrier considered that these dimensions of workplace design corresponded to the properties identified in HRO research. Despite having very different workplace designs, in her opinion, the two NPPs that she assessed had operated as HROs. However, she also contended that HRO research had not focussed sufficiently on the way in which HROs emerge out of the behaviour of their workers, an important aspect of her findings from the two NPPs. Therefore, it is worthwhile, to consider these characteristics of HROs more fully, as potential criteria for assessing human factors in maintenance reliability.

2.11.3 The high-reliability organisation

Researchers have investigated high-risk operations, such as petroleum production (Øien, 2001a), medicine (McKeon, Cunningham, & Oswaks, 2009), military units (Roberts, Rousseau, & La Porte, 1994), aviation and NPPs (Klein, Bigley, & Roberts, 1995) in order to understand how these operations managed to avoid failures in organisational systems. Their work led to the development of High-Reliability Theory (HRT) and the concept of the High-Reliability Organisation (Roberts, Rousseau, & La Porte, 1994; Klein, Bigley, & Roberts, 1995). Researchers such as Rochlin (1999) attempted to establish the generic characteristics that define HROs, rather than focus on the reliability of specific tasks in a particular workplace. He observed that a range of types of HROs, e.g. air traffic control operations, military operations, and nuclear power generation, were characterised by a focus on risk, continuous learning at all levels of the organisation, and efforts to maintain communication. The features of HROs were further evaluated by Vogus and Welbourne (2003) in their study of 184 software firms. They hypothesised that the latent dimensions mediating between the workforce and company performance were *Emphasis on training*, *Commitment to resilience*, and a *Reluctance to simplify interpretations*. La Porte (1996) also formulated a conceptual framework around his observations of the internal processes and external relationships that characterised large HROs. Concerning the internal processes, he observed that consideration of the consistency of processes was of equal importance to the performance of objectives. This was accompanied by a high level of operator autonomy, including considerable decision-making at lower levels in the organisation. At the same time, relationships with the external environment were intensely managed in order to maintain the support and trust of outside agencies, such as regulators and community groups. As a result of these studies, a theoretical understanding of a collection of organisational characteristics came to be accepted as constituting an HRO. Roberts, Rousseau, and La Porte (1994) adopted a more empirical approach to determining if the characteristics of an HRO were present on a U.S. Navy vessel. Using the Organizational Culture Index (OCI), they determined that the officers and enlisted men registered a high level of satisfaction with both the high task demands and high control of behaviour. In this HRO, the reliability of processes was considered to be of greater importance than the reliability of outcomes. Klein, Bigley, and Roberts (1995) used the same instrument to examine organisational cultures in two distinct types of HROs. In this study, the U.S. Air Traffic Control system achieved its high reliability through an ability to reduce tight-coupling and interdependence in an emergency. They referred to this system as a *decomposable HRO*. In contrast, the NPP in the study achieved high reliability by maintaining a high level of coordination of organisational systems, referring to this as a *holistic HRO*. As Bourrier (1996) observed, it is possible for different workplace models to support high operating reliability.

The research on HROs demonstrated that remaining within the boundaries of reliable operation required a greater level of cognitive ability, situation awareness, and operating experience on the part of workers, compared with organisations that are based on less-hazardous technology. These sources of reliability in the workplace are responsible for what Weick (1987) termed ‘dynamic non-events’, that is, successful processes in an ever-changing workplace. Furthermore, as noted earlier, the position of these boundaries is a function of organisational constraints and tends to drift under organisational pressures, such as time and financial constraints (Rasmussen, 1997a), and political imperatives (Sagan, 1994). Thus, in Rasmussen’s model, workloads and economic pressures will tend to drive organisationally accepted safety limits into the marginal areas of safe operation and towards a higher probability of accidents.

As the researchers studying the management of hazardous technologies such as petroleum production have realised, resolving problems in technically-complex and tightly-coupled systems required consideration of workforce/technology interactions (Heimann, 2005) within a framework based on an understanding of human factors.

In turn, many of the theoretical advances in understanding the role of human factors in workplace effectiveness have developed out of this realisation and empirical studies of organisations that could be considered as HROs. A further stage in this process would be to identify those factors that have the greatest influence on maintenance reliability, and to quantify the extent of their influence. This is, in fact, the basis for the three studies in the current research.

2.12 Summary of Existing Research

As the literature examined in this chapter demonstrated, maintenance reliability is an important issue for any organisation which depends for its success on the predictable operation of facilities and equipment. This is particularly the case for hazardous technologies, such as petroleum production, in which failures can have severe implications for workgroup, community, and environmental safety (Pate-Cornell, 1993).

Ensuring the reliability of complex equipment has traditionally been viewed as a matter of technical concern (Dhillon, 2002); that is, the solution to faults and failures lies in improving the technology employed. Consequently, much research has focussed on the contribution of engineering design to failures, with estimates (Taylor, 2007) that 55% of failures in process industries could be attributed to design flaws. However, despite a solely technical approach prevailing in much of the engineering literature, researchers (Crichton, 2005; Flin, O'Connor, Mearns, & Gordon, 1999) studying petroleum operations began to consider the human factors in maintenance-related failures and in the potential for disasters. Typical industry figures quoted (Reason & Hobbs, 2003) for maintenance failures associated with human performance were in the range of 42-65%. Studies cited in the literature have demonstrated that many instances of failures and accidents are the result of not considering the human element in the maintainability of equipment. Practitioners in maintenance reliability in the petroleum industry (Bea, 1998; Øien, 2001a) have therefore recognised that the non-technical contributors to reliability need to be considered alongside the technical factors.

The influences on maintenance reliability, as with other indicators of organisational performance, can be conceptualised as situated at the individual-, group- or organisational-levels (Figure 2). At the individual level, human error and procedural violations have long been the concern of both researchers (Khan, Amyotte, & DiMattia, 2006) and accident investigators (Sklet, 2006) in petroleum operations. In these hazardous, tightly-coupled workplaces they were seen as the immediate pre-cursors to accidents. Other individual level factors considered likely to be important to maintenance reliability were affective factors, including motivation, commitment, and job satisfaction.

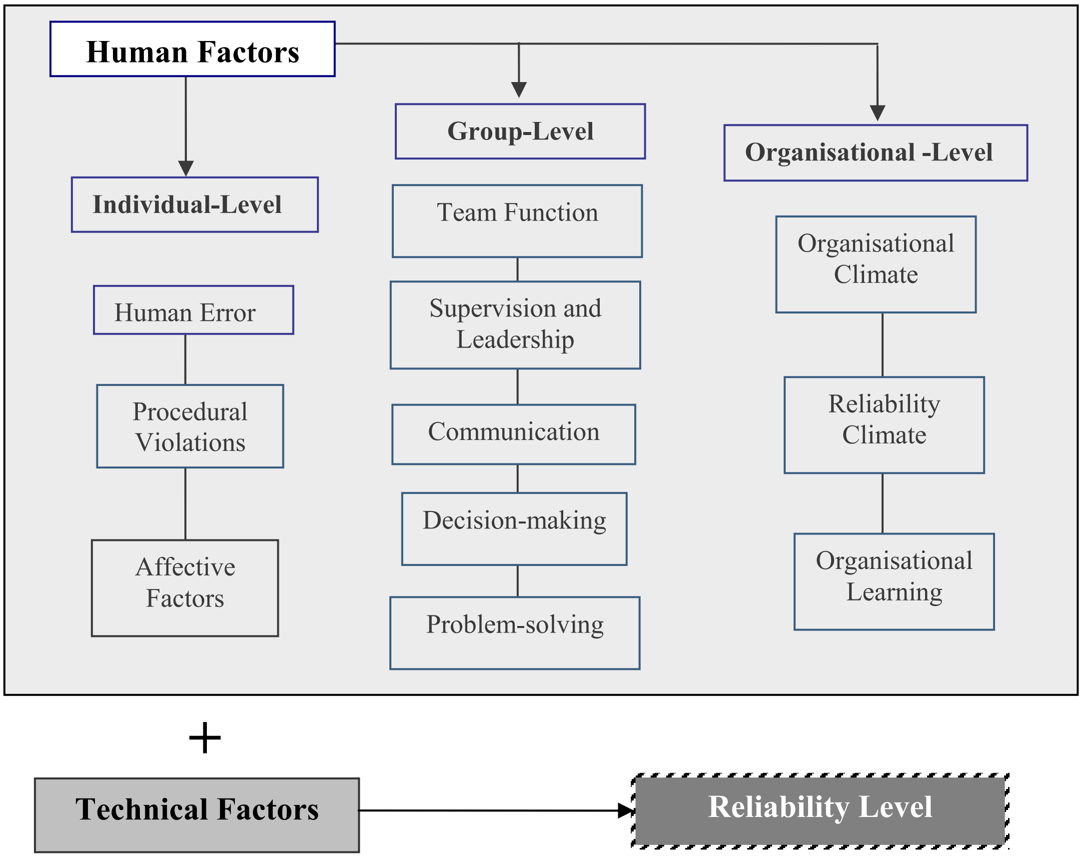

Figure 2. Summary of factors expected to influence maintenance reliability

Further research cited, particularly in the field of industrial maintenance and safety (Zohar & Luria, 2003b), demonstrated the need to address the underlying causes of these errors, violations, and affective reactions through understanding of group-level and organisational-level processes. Among these group-level processes identified in the literature were team functions, supervision, and leadership, communication, decision-making, and problem-solving. A number of studies in the petroleum industry and many others in comparably hazardous industries have identified the important role of team functions (Crichton, 2005), communication (O'Connor & Flin, 2003), and supervision (O'Dea & Flin, 2001) in supporting the activities of maintenance personnel. As examples, mutual error checking within teams, the style of leadership used, and effective communication between team members were all group-level factors demonstrated to influence workplace performance. These processes in turn supported the output of maintenance work-groups in the form of decision-making and problem-solving. The prevalence of Recognition-Primed Decision-making in operating environments (Carvalho, dos Santos, & Vidal, 2005), and the possible need for more analytical decision-making and higher-order problem-solving in maintenance activities were also examined by researchers (Hokstad, Øien, & Reinertsen, 1998; Schaafstal, Schraagen, & van Berlo, 2000).

Studies of organisational-level processes demonstrated their critical role in supporting the work of maintenance personnel. Workplaces, particularly in complex socio-technical systems, needed to be designed from the beginning with consideration of the human factors as well as the technical factors (Bourrier, 2005). These designs were dependent on an understanding of the core tasks of the maintenance workplace (Oedewald & Reiman, 2002), out of which evolved its organisational climate. Among these dimensions of a climate that created reliability, was an ability of the organisation to learn from its failures and the solutions to these failures (Tucker, Edmondson, & Spear, 2002). Organisational Learning was considered to be critical to workplace performance (Carroll, 1998), especially in complex organisations, where interdependencies between systems and tight coupling of human-machine and machine-machine interactions magnified the effects of any weaknesses in organisational processes. Pioneers in the field of human factors have attempted to model the effects of these weaknesses in organisational systems as a means of understanding the basis for reliability. This has given rise to the concepts of Defences-in-Depth (Reason & Hobbs, 2003), the Human Malfunction model (Rasmussen et al., 1981), the Systemic Accident Model (Hollnagel, 2002) and the Drift Into Failure model (Dekker, 2005). These models demonstrated in various ways the mechanisms through which organisational processes supported reliability or contributed to failures of human work activities.

As a result of this increased understanding of the organisational processes mentioned above, as well as concerns about managing hazardous industries (Heimann, 2005) such as petroleum production (Øien, 2001a), there have been numerous investigations into the dimensions that are responsible for their relative success (e.g., Rochlin, 1999). Attempts to characterise the common elements have given rise to the concept of the HRO (La Porte, 1996), which was intended to serve as a model for structuring organisations that are responsible for operating hazardous technologies. Consideration of the HRO has highlighted the importance of understanding human factors at all levels in an organisation in order to ensure reliable performance (Vogus & Welbourne, 2003).

Although a number of studies relating to reliability in the petroleum industry were identified, many of the advances in understanding were derived from studies of maintenance in other hazardous industries. In addition, the importance of understanding human factors and their potential influence on maintenance reliability were frequently discussed in the literature cited, but it has not been clear which among these human factors have the greatest impact on maintenance reliability in the context of petroleum production, or how strong the association may be between specific human factors and measurable outcomes. In the next chapter, a rationale for continuing the investigation of contributors to maintenance reliability in petroleum operations will be provided, as well as the need for research to quantify the relationship between reliability and specific human factors.

3.0 Research Rationale

3.1 Past Research

As discussed in Section 2.3, maintenance reliability is defined as the probability of failure-free operation of equipment and plant. Literature cited in Section 2.7 has demonstrated that many instances of maintenance failure are the result of not considering the maintainability of technical equipment in the original designs of production systems. In addition, researchers studying both equipment reliability, as well as major disasters, have recognised that the human factors contributing to failures related to maintenance need to be considered alongside the technical factors. Many researchers (Section 2.11) have examined the human factors in failures, and based on these events, developed models of the processes involved, and conceptualised the requirements for maintaining high reliability in operations.

In order to understand the requirements for high reliability, as well as the contributors to failures, past studies have examined human factors at the individual-, group- and organisational-levels (Figure 2). At the individual level, human error and procedural violations were frequently investigated (Section 2.8) as the contributors to failures of technical systems, through the actions of humans in the design, operation, and maintenance of these systems. However, research, particularly in the field of process safety (Section 2.11.1), has demonstrated the need to address the underlying causes of these errors and violations through an understanding of group-level and organisational-level processes. Literature from the petroleum industry has examined such group-level factors (Section 2.9) as teamwork, communication, decision-making, and problem-solving. These group-level factors were in turn described as being influenced by organisational-level factors (see Section 2.10) including 1) the design of workplaces, 2) the emergence of various organisational climates, and 3) the ability of an organisation to learn from events. The incorporation of these group-level and organisational-level dimensions into Crew Resource Management training in the petroleum industry has demonstrated the importance that they have in regard to reliability and process safety.

3.2 Justification for Conducting Further Research

3.2.1 Importance of research in petroleum industry operations

As discussed in Section 2.4, research into the factors responsible for reliability in petroleum production is of interest to the petroleum industry due to the hazardous operating environment, coupled with the high value of production. Reliability levels influence the probability of failure, and consequently, affect the productivity as well as the costs of maintaining this production, which was estimated to be approximately 30% of production costs for a large petroleum producer. At the same time as there are financial benefits for successful petroleum producers, there is also the potential for an explosion or environmental release of hydrocarbons, as was witnessed in the destruction of the Deepwater Horizon (Urbina, 2010) and Piper Alpha (Pate-Cornell, 1993) platforms, and in other petroleum industry disasters (Sovacool, 2008). Aside from the damage and injury which could occur in a serious accident, the loss of fuel supply for an extended time has significant economic implications for the broader community, as described in Section 2.4. Therefore, advances in the area of reliability offer an opportunity for both less costly and safer operation for producers, and security of supply for the community. Research to understand the contributing factors in production losses also represents a means of identifying the impediments to maintenance activities and improving the effectiveness of these activities.

3.2.2 Need for further research on human factors in hazardous workplaces

As petroleum operations become more reliant on technology that is in turn based on complex human-machine interactions, further research is needed in the field of human factors to understand how their reliability might be enhanced. The flaws in human-machine and human-system interactions are exacerbated by the tight couplings and dependencies created through the design of automation and control systems, and a prevailing tendency to use advanced technologies to minimise human intervention (see Section 2.11). An example of this type of flawed human-system interaction in a socio-technical system was the explosion and oil release at the Deepwater Horizon oil rig in the Gulf of Mexico. Professor Patzek in the Petroleum and Geo-systems Engineering Department of the University of Texas was quoted (Urbina, 2010) as describing the oil rig as, “a very complex operation in which the human element has not been aligned with the complexity of the system.” The tight couplings and interdependencies of humans and complex technology have been similarly recognised as risk factors in other research into petroleum operations (Øien, 2001a; Øien, 2001b). There is a justification therefore, for extending current knowledge concerning the role of human factors in petroleum operations by applying learnings gained in other hazardous industries, such as aviation and nuclear power generation.

Comparisons between industries have been shown to be useful in exploring the influence of the human factors common to the hazardous industries. For example, despite the contextual differences, comparative research between air traffic management and nuclear power generation (Straeter & Kirwan, 2002) and between medicine and aviation (Sexton, Thomas, & Helmreich, 2000) has provided indications of the areas in which progress in human factors can be achieved. Many of the factors of importance in reliability in these domains, such as decision-making and communication, are expected to be relevant to petroleum production operations. In terms of maintenance in a production context involving heavy machinery, complicated process-control equipment, and containment of high energy sources, the petroleum industry is likely to be analogous to the nuclear power industry. The maintenance activities required in both industries are expected to place similar physical and cognitive demands on maintenance workers.

Despite these apparent similarities between maintenance tasks and roles in the petroleum industry and nuclear power industry, there are also a number of domain-dependent differences that justify research that is specific to the petroleum industry. First, due to public concern with accidents involving nuclear power plants, the industry is closely regulated by government agencies, and the maintenance activities are highly proceduralised compared to maintenance in the petroleum industry. As a consequence, much of the attention in human factors studies of the nuclear power industry has been on human error, as well as accidental and deliberate violations of regulatory and operational procedures (Munipov, 1992). In contrast, the petroleum industry has been less-regulated and has tended to operate more autonomously (Urbina, 2010).

Furthermore, the difficulties of access to off-shore petroleum facilities, and the wide geographical distribution of these facilities, provide additional constraints relating to human factors in the workplace, particularly with organisational communication and the supervision of workers. Maintenance teams can be responsible for a variety of production systems, often under changing operational conditions, with a wide range of failure modes. As a result, many areas of the petroleum industry rely on a high level of workgroup autonomy, with fewer established procedures. Autonomy implies a greater reliance on decision-making and problem-solving processes among the workforce. In addition, a high degree of mobility among petroleum industry personnel in Australia means that behaviours relating to teamwork, communication, and organisational learning may be more important factors than in industries that are not as geographically distributed. These differences between organisational structures and activities in the petroleum industry, compared to other potentially hazardous industries, justify the need for an investigation of the role of human factors in this domain.

Finally, past research in the petroleum industry has tended to focus on a limited number of human factors, such as teamwork and leadership (e.g., Crichton, 2005). It has also often been the case that the human factors examined are those that relate to the safety of workers. Although the role of human factors in achieving a *safety culture* in the petroleum industry has been well-documented (Flin, Mearns, O'Connor, & Bryden, 2000), the role of human factors in achieving a *reliability culture* in this industry has not been as clearly delineated in the literature reviewed. As discussed in Section 2.10.1, the need to avoid injuries has often generated a focus on particular risk factors, which may be different to the risk factors in maintaining reliable operations. For example, as a consequence of the concern with the safety of workers, research on leadership and decision-making (O'Dea & Flin, 2001) and failure investigation methods (e.g., Gordon, Mearns, & Flin, 2000) have tended to predominate over consideration of other factors, such as organisational communication, problem-solving behaviour, and organisational learning, which may be equally relevant. Research into a broader range of factors is warranted to provide guidance for future interventions aimed at improving reliability. For these interventions to be effective, it is important that they be targeted towards risk factors specific to the petroleum industry, rather than towards generic factors which are presumed to influence all organisational outcomes.

3.2.3 Benefits: development of theoretical concepts

The framework for the current studies is based on models of systemic failure within organisations as reviewed in Section 2.11.1. These provide a basis for conceptualising the mechanisms through which industrial failures might occur. Analyses of workplace events would assist in demonstrating whether these models are appropriate means of categorising and explaining observations relating to failures in petroleum maintenance operations.

Similarly, the concept of reliability relies on engineering models that are based on the probability of failure-free operation of technical equipment and operations (see Section 2.5). These models are used to underpin engineering designs and analyses of the maintainability of critical equipment. Many of the theoretical reliability models refer to failure rates of individual components and machinery, often relying on estimations of failure rates (Todinov, 2004). In order to conduct the current research, collection of data was needed based on the reliability level of entire work areas. Consequently, a benefit of the current studies is in demonstrating that reliability measures based on theory are able to provide a valid means of differentiating reliability outcomes between similar work areas.

3.2.4 Benefits: development of practical measures

In addition to advancing theoretical understanding of the mechanisms of reliability in an industrial context, industry-based research should also produce practical benefits. One of the potential outcomes of this project is a refinement of methodologies for investigating maintenance-related failures. Researchers consider that analysis of incidents is critical to understanding the interactions between factors that may occur in unexpected failures (see Section 2.11.1). A benefit of this research will be to evaluate investigation tools of potential use in identifying human factors in failures in a petroleum industry context.

There have been efforts to analyse improvements to organisational reliability based on a human factors approach, particularly in HROs (Vogus & Welbourne, 2003; Klein, Bigley, & Roberts, 1995). However, these studies have generally relied on qualitative assessments of reliability (La Porte, 1996). Even when quantitative measurements were made of the human factors in an organisation (Roberts, Rousseau, & La Porte, 1994), there do not appear to have been equivalent quantitative measures of task performance. Therefore, it is not clear which among the various human factors have the greatest impact on maintenance reliability in a particular domain, and how strong the association may be between specific factors and measurable outcomes. As Reiman and Oedewald (2004) commented in relation to the aims of their own CULTURE survey of the maintenance culture in Scandinavian NPPs,

> The research did not aim at finding performance indicators or other objective characteristics to validate the connection of the results to the operational reliability of the plant…Further research should aim at clarifying the influence of organisational culture [on] objective measures of plant reliability. (p.886)

In Reiman and Oedewald's (2006a&b; 2007) numerous assessments of maintenance climate, a framework was developed for linking specific factors to maintenance outcomes. The current thesis is intended to advance the theory and practical investigations of researchers such as Reiman and Oedewald, by identifying a suitable measure of reliability and then determining if statistically significant relationships exist between this measure and specific human factors. If relationships can be identified, then these measures can be used to develop practical interventions based on a human factors approach to maintenance reliability, and to demonstrate the benefits that can be achieved. Demonstrating the measurable role of human factors in reliability will then provide a further impetus for integrating a human factors approach with an engineering approach to solve problems in the reliability of technically-advanced operations.

A further benefit of this research will be to advance the awareness of the value of a human factors approach in designing facilities and specifying maintenance activities. It is hoped that in addition to gains in the efficiency and effectiveness of maintenance workgroups, this research will also encourage a conceptually broader and more human-focussed approach to maintenance management.

3.3 Research Aim and Objectives

3.3.1 Overall research aim

The literature surveyed in Chapter 2 showed that the impact of specific human factors on reliability in maintenance work was of sufficient interest to warrant further investigation. The overall aim of this thesis is then to identify the human factors that have the most influence on maintenance reliability in the petroleum industry, and determine their quantitative relationship with outcomes.

3.3.2 Specific research objectives

Based on models of failure in socio-technical systems (see Section 2.11.1), the human factors contributing to maintenance failure will be investigated in the context of petroleum maintenance operations. As was the case with studies of maintenance performance in the aviation (Hobbs, 2000; Latorella & Prabhu, 2000), railway (Holmgren, 2005), and nuclear power (Pyy, 2001) industries, the starting point for understanding maintenance reliability in the petroleum industry will be a detailed study of the human factors that were extant when maintenance failures occurred. To identify the human factors contributors to these incidents, Study 1 examines the data that the target organisation has collected as reports of adverse events, and Study 2 analyses the data derived from structured interviews with maintenance personnel.

A failure investigation taxonomy is needed to accomplish this objective of analysing past failures. As explained in Section 2.8.3, many of the developments in the field of human factors have been based on frameworks for categorising erroneous human actions and flawed organisational processes. An objective of the current research is to select a taxonomy from among those that have been developed in the course of human factors research (e.g., Reason, Parker, & Lawton, 1998; Marx, 1998), and adapt it to studies of failures in petroleum operations.

Research objective of Study 1: To determine the human factors that appeared most frequently in company-based reports of maintenance-related failures in petroleum industry operations. A secondary objective of Study 1 is to select and refine a taxonomy for analysing the human factors contributors to maintenance-related failures.

Research objective of Study 2: To determine the human factors that contributed most frequently to maintenance-related failures in petroleum industry operations based on structured interviews with maintenance personnel.

Once the most-frequent contributors to past maintenance failures in the target organisation have been identified in Studies 1 and 2, the objective of Study 3 is to evaluate the human factors characteristics of higher and lower reliability work areas in a petroleum production company. Therefore, one objective is to select an appropriate measure for comparing reliability levels that would be commensurate with current principles of maintenance reliability engineering (Dhillon, 2002; International Standards Organization, 2006b). Another objective of Study 3 is to determine if higher and lower reliability work areas can be differentiated on the basis of their human factors characteristics. This necessitates selecting appropriate, reliable, and validated scales for measuring the perceptions of maintenance personnel regarding the predominant human factors that were identified in Study 2. In addition, a qualitative analysis of the perceptions of maintenance personnel, concerning the influences on reliability in their work areas, is beneficial in supporting the data derived from quantitative measures. This additional data will provide a means of triangulating quantitative data in order to reduce the potential for bias from using a single method of data collection.

Research objective of Study 3: To determine if higher and lower reliability work areas in the target organisation could be differentiated by the perceptions of maintenance personnel concerning the human factors identified in Study 2 as contributing most-frequently to maintenance-related failures. A secondary objective is to use qualitative data to triangulate the quantitative data from the survey in Study 3, in order to aid in the interpretation of the inferential analyses in Study 3.

4.0 Study 1: Investigating Human Factors in Company Incident Reports

4.1 Introduction

Study 1 involves the selection and refinement of a taxonomy for analysing the mechanisms of maintenance failures in a petroleum industry operation, and the application of this method to determine the human factors that appeared most frequently in company-based reports of maintenance-related failures.

4.1.1 Framework for Study 1

As discussed in Section 2.11.1, a framework is required to make sense of the decisions and actions of individuals in their workplace. A useful framework provides a basis for understanding the mechanisms expected in the particular domain being investigated. Since Rasmussen described his Human Malfunction model in 1982, many researchers (e.g., Reinach & Viale, 2006; Hobbs & Williamson, 2002; Gordon, Flin, & Mearns, 2005) have made use of this model to investigate the role of human factors in failures of safety and reliability. This model, in conjunction with his (Rasmussen, 1997a) concept of drift across boundaries of safety limits and safe operation, provided a far-reaching frame of reference with which to assess the mechanisms whereby human factors contribute to failures in an industrial context. The two models conceptualised the individual maintenance technician not as an independent entity entirely responsible for outcomes, but as a participant in a dynamic system, engineered for reliability, but subject to drift towards failure under organisational pressures. This has changed the focus to a conceptual realm in which individual performance intersects with engineering design and workplace systems. It is in considering the role of these three aspects of the workplace that the strength of the Human Malfunction model serves as a comprehensive basis for understanding the mechanics underlying maintenance reliability in technology-based systems.

4.1.2 Taxonomies of failure

Rasmussen et al (1981) provided advice on how research might quantify the contributors to failure:

> To be able to quantify the frequency of inappropriate human acts in a meaningful way, it is necessary to separate cases of intrinsic human variability and spontaneous human errors from cases of psychologically normal human reactions to external events or changes in the work situation,

> This means that a simple classification of human errors with reference to the task sequence in terms of omission, commission, timing errors etc. is not adequate. Careful efforts should be spent to identify potential external causes with reference to categories which allow estimates of frequencies in another particular situation. (p. 5)

One approach to determining the predominant contributors to accidents has been through the development of investigation methodologies for characterising the human factors responsible for reliability-related incidents, such as maintenance failures. Taxonomies have been created for describing and categorising the various contributors to outcomes, both positive and negative, deriving from human-machine and human-task interactions. Taxonomy logically evolves out of the framework adopted for observing and understanding these interactions. Therefore, the taxonomy for Study 1 must be consistent with the framework, while capturing the various workplace behaviours related to desired maintenance outcomes (Ross, Wallace, & Davies, 2004).

Two crucial tasks in developing failure investigation methods are the selection of taxonomy and the application of the taxonomy to failures. There has been a tendency apparent in the literature to consider the technical, individual, and organisational aspects separately in a way that depends on the field of investigation of the researcher. Put another way, in Dekker's (2006) discussion of accident models he warns that the model selected will depend on how the investigating organisation believes that accidents occur, which in turn will tend to dictate what causes are identified. For example, a commonly used technique for analysing potential causes of failure in a system is known as Failure Modes and Effects Analysis (FMEA) (Moubray, 1997). Referring to the way that maintenance analysts conduct this analysis, Moubray commented, "Some even go so far as to specify that FMEA's…should deal only with failure modes caused by deterioration and should ignore other categories of failure modes (such as human factors and design flaws)" (p. 58). Wallace and Ross (2006) explained that a danger in the use of taxonomic systems to categorise human errors is that low inter-rater reliabilities can occur due to differing frames of reference, either between raters with differing backgrounds, or between raters and the developer of the taxonomy.

Due to differing frames of reference in different industries, a common approach to analysing human factors in incidents has been through the development of industry-specific failure investigation taxonomies. These provide a basis for categorising the human factors responsible for maintenance failures and other reliability-related incidents, and thereby attempt to provide an understanding of the mechanisms of failure, within a frame of reference. A number of industries have designed investigation tools for accident investigators operating in a specific domain, including:

- British Airways’ Human Factor Reporting Programme (O'Leary, 2002).
- Human Factors Analysis and Classification System (HFACS) for use in military aviation (Shappell, 2000) and rail operations (Reinach & Viale, 2006).
- Human Error Reduction in Air Traffic Management (HERA) and JANUS techniques (Pounds & Isaac, 2003) developed for air traffic management (ATM) using a structured interview approach to retrospectively analyse past incidents.
- U.S. Department of Energy’s (1999) Accident Investigation Program for nuclear power plant investigations.
- Human Factors Investigation Tool (HFIT) developed for the North Sea petroleum industry (Gordon, Mearns, & Flin, 2000).

Each of the above provides a taxonomy that is relevant to a specific field of practice and is based on an existing conceptual approach to the causes of failure recognised by that field of practice, which Hughes’ (1951) termed a ‘jurisprudence of mistakes.’

4.1.3 Justification for selecting HFIT investigation taxonomy

Gordon, Flin and Mearns (2005) developed the Human Factors Investigation Tool (HFIT) in an effort to utilise the elements of Rasmussen’s Human Malfunction model, as well as to integrate other applicable elements found in existing investigation taxonomies into an appropriate investigation tool for the offshore petroleum industry (Gordon, 1998). With HFIT, they succeeded in translating a number of theoretical constructs of human factors into a practical instrument for conducting detailed investigations into failures and accidents. It was intended for use by engineers and other investigators in the petroleum industry, who would have varying degrees of expertise in human factors. This is in contrast to the other investigation tools listed above which were designed for use by human factors specialists in the respective fields of aviation, rail operations, air traffic control, and nuclear power production. HFIT was selected for the current research as it is both relevant to the petroleum industry and depends for its underpinnings on Rasmussen's framework, which is the frame of reference that has been adopted for this study.

HFIT provided for consideration of a comprehensive range of human cognition, performance-shaping, and error-promoting factors described in Sections 2.8-2.10 as influences in the workplace. These influences are represented by the major categories in HFIT of *Situation Awareness*, *Action Errors*, and *Organisational Threats*. A further strength of HFIT lies in adopting a multi-level approach to analysing the factors associated with failures (see Section 2.8.1). Such a multi-level approach to workplace factors is supported by Zohar and Luria's (2005) research into industrial safety. Their hypothesis was that safety drivers can reside at any of the three organisational levels within the work environment, namely the individual, the workgroup, or the organisational level. An accident analysis then proceeds from consideration of the contribution of each of these levels. Similarly, HFIT is structured in such a way as to allow an analysis of the individual, workgroup, and organisational contributors to a failure under investigation. At the individual level are dimensions such as *Omission, Violation,* and *Work Quality*. The workgroup level includes the dimensions of *Teamwork*, *Supervision,* and *Communication,* while the organisational level includes *Procedures, Organisational Culture,* and *Work Environment*.

A complete human factors based investigation of a maintenance failure required both an understanding of the workplace factors experienced at the time by maintenance personnel, as well as an empirical assessment of the dimensions of the organisation that could be observed and analysed via descriptions of past events. The HFIT taxonomy and format provided a suitable instrument for accomplishing this task.

4.1.4 Research setting: The target organisation

The research setting for this study was a large, independent producer of oil and gas products in Australia. Products produced include liquefied natural gas (LNG), liquid petroleum gas (LPG), condensate, and oil. The organisation considers itself as a "*reliable supplier* [italics added] with a focus on delivering on our commitments". As such, it was deemed a suitable candidate for determining the extent to which this reliability of supply was influenced by human factors.

The target organisation is composed of three distinct types of production facilities, i.e. off-shore gas platforms, off-shore Floating Production, Storage and Offloading (FPSO) vessels, and an on-shore gas processing plant (the Process Plant). The gas platforms are larger, more complex faculties processing gas from undersea wells. The FPSOs are simpler facilities built into ships, and designed to extract oil and pump it into oil tankers for refining elsewhere. The Process Plant consists of a number of production trains that separate and process gas from off-shore wells and other operational areas. Liquefied natural gas is stored and loaded into LNG tankers for export, while Liquefied Petroleum Gas is piped to communities for domestic consumption (DomGas).

There are a number of examples of each type of facility within the company, providing an opportunity for within-group and between-group experimental designs. The maintenance workforce includes both maintenance technicians directly employed by the company and contractors who work for third-party companies that supply services. In addition, there are Core Crews who are based on the facilities, and Major Maintenance crews that are based at the geographically-separated central administration, and brought on-site for specialised shutdown activities. The maintenance work required is divided between electrical / instrumentation maintenance and mechanical maintenance activities. These distinctions provide a further level of analysis between different types of work processes, involving both basic and more technically-advanced task procedures.

These technologically-advanced processes are conducted in production facilities that are complex and hazardous in terms of both worker-safety and the potential for major facility and environmental disasters. As such, petroleum production represents a high-level of safety-criticality, but has not been researched as thoroughly as, for example, commercial aviation and nuclear power plant operations. In contrast to these other hazardous industries, petroleum production is less subject to regulation by government authorities and workplaces are more widely-distributed geographically. For these reasons, petroleum operations are a distinctly different type of work environment, offering an alternative view of the role of human factors in the workplace.

As discussed in Section 3.2.1, maintenance personnel in the petroleum industry tend to have a higher degree of autonomy in their day-to-day activities than in many other hazardous industries. With more discretion in determining how tasks are to be done, and less regulatory over-sight, there is a greater range of acceptable practice. Consequently maintenance technicians have more individual responsibility for interpretation of information and decision-making within their job function. Petroleum processing is therefore an ideal environment for studying the impact of human factors in critical situations in which workers have a greater level of control over work processes. The consequences of incorrect behaviours and decisions in petroleum production can be almost as severe as in a nuclear power plant, but the levels of workplace control are more akin to that in general industry. Altogether, the particular characteristics of the target organisation provide an opportunity for understanding of the role of human factors in an industry that warrants further study.

4.1.5 Summary of objectives

Based on the considerations described above, the principal objective of Study 1 was to identify the human factors that were most-frequently mentioned in company-based reports of maintenance-related failures in petroleum production operations. A secondary objective of Study 1 was to select and refine a taxonomy for analysing the human factors contributing to maintenance failures. This taxonomy was required to be consistent with Rasmussen's Human Malfunction model and be appropriate for the petroleum industry domain.

4.2 Method

4.2.1 Sample

Adverse events, hazards, and investigated failures are recorded in the company's Information Management system in an incident reporting database called *First Priority*. It is described on the entry screen as an "enterprise-level compliance, risk, and knowledge management system." First Priority records the significant operational failures that have resulted in production losses, equipment damage, environmental threats, and personal injuries occurring throughout the company. Data is submitted by incident investigators via both on-line and on various versions of paper-based incident recording forms. Supplementary material, which includes more detailed, follow-up investigations, is often appended to the forms.

The entries in the First Priority database were examined for one calendar year, namely 2007, the first full year of this research. Of interest in the current research were the entries in First Priority categorised as *Incident - Asset Damage and Lost Production*. This is the category reflecting the outcomes of maintenance and operating practices within the various facility workgroups. Other categories in First Priority are:

- *Incident-People.*
- *Incident-Reputation.*
- *Incident-Environment.*

There are also categories for recording identified hazards which do not eventuate as incidents.

4.2.2 Measure

HFIT was designed as a comprehensive accident investigation method, and, as it is currently configured (Gordon, 2001), consists of 54 pages of queries arranged into flow charts. HFIT is structured as an 'expert system', which leads the investigator through a series of topics and questions covering the possible human factors involved in a failure or accident sequence. The analysis leads from the more general, over-arching organisational issues to the specific group and individual level details of the incident or accident. In HFIT, consideration of multiple levels is achieved by considering the three organisational levels influencing an event. The major categories specified in HFIT are *Action Errors, Situation Awareness,* and *Organisational Threats*.

Action Errors refer to the immediate actions undertaken preceding the failure. These generally relate closely to the actions of individual workers, and included errors of omission and commission, violations of procedures and poor work quality. Codes in the category of *Situation Awareness*, such as *Assumption* or *Decision-making*, tend to directly precede the failure. A loss of situation awareness may also evolve over time prior to the fault occurring, as with a progressive loss of attention due to fatigue or a failure to detect prior warning signals (O'Leary, 2002). On first consideration, aspects of *Situation Awareness* in HFIT appear to relate mainly to the individual. However, the codes pertaining to *Situation Awareness*, such as *Detection, Assumption, Interpretation,* and *Decision-making*, have been described by Stasser and Stewart (1992) as at least socially-influenced, if not a direct outcome of group thinking. The literature on shared mental models (Mathieu, Goodwin, Heffner, Salas, & Cannon-Bowers, 2000) and detection of team-based errors (Sasou & Reason, 1999) would also suggest a greater influence at the workgroup level.

Finally, the most temporally distant, and organisationally distributed are the *Organisational Threats*. They include such organisational dimensions as leadership, training, planning, organisational learning, teamwork, and communication. These are often depicted as containing latent and omnipresent pathogens in the local workplace (Reason, Parker, & Lawton, 1998), if not across the whole organisation. Effectively, these are the holes in Reason's Defences-In-Depth (see Section 2.11.1), which remain latent over a period of time within organisational functions. They can be expected to contribute to a wide range of failure types. As such, they are the most difficult to both identify and correct. Issues such as technical design, work environment, organisational culture, and work procedures represent fundamental organisational processes that are generally controlled at the highest levels of the organisation. HFIT also provides codes for *Error Recovery* (detection, indication, and correction). However, as the concern of Study 1 was events that eventuated as failures, *Error Recovery* categories were not coded.

Altogether, a broad range of organisational, workplace and performance-shaping factors are considered in HFIT. Most are squarely situated in the human-system interface, in other words, where the organisational and work environment impact on the individual's ability to make decisions and act. The varieties of human behaviour required to control and maintain modern technology in the petroleum industry, called Requisite Variety by several authors (Reason, Parker, & Lawton, 1998; Zohar & Luria, 2003b), meant that there was a large pool of potential failure modes involving workers. Capturing and analysing these factors required a taxonomy with a comprehensive, but manageable range of descriptive codes. The codes in the HFIT model provided sufficient differentiation for a detailed taxonomic analysis covering most of the concepts in the Human Malfunction model.

4.2.2.1 Validity and reliability of HFIT

As a part of the development of HFIT, the validity of the constructs involved and the inter-rater reliability were evaluated (Gordon, Flin, & Mearns, 2005). HFIT was tested in trial investigations of an incident, by four oil and gas exploration companies and the UK Health and Safety Executive. The inter-rater agreement between investigators (r_{wg}) was recorded for each of the 27 codes surveyed in HFIT. Of these, there was good agreement ($r_{wg} > 0.66$) for six items, moderate agreement ($0.33 \leq r_{wg} \leq 0.66$) for six items, and poor agreement ($r_{wg} < 0.33$) for 15 items. Gordon et al believed that the low inter-rater reliability for some of the items might have been because the users were mainly engineers who had had experience with accident investigations, but only a limited background in human factors. However, an additional factor in low inter-rater reliability may have been differences in interpretation by the raters of interviewee responses. Wallace & Ross (2006) contended that differing frames of reference are one of the main causes of variability in inter-rater reliability.

Validity was determined by asking the 25 experienced investigators who trialled HFIT to evaluate the HFIT model using a series of criteria. Based on four questions, such as "Is the model a technically sound framework that can test the quality, validity, and relationships of data developed during an investigation" (p. 166), the authors concluded that "the majority of investigators reported that HFIT addresses the key causes of incidents" (p. 162).

From the validity testing of HFIT by Gordon et al (2005), most of the 25 investigators confirmed that the items in the investigation tool had construct validity. Regarding face validity, the items in HFIT appeared to describe clearly situations that could potentially contribute to an incident according to the Human Malfunction model. However, the low inter-rater reliability data for 15 items indicated that discriminant validity might not have been sufficiently high. As a result, the individual items in HFIT were examined as part of the current research to determine which items might be ambiguous and could lead to disagreement between raters.

4.2.2.2 Adapting HFIT for Study 1

To address the issue of inter-rater reliability in HFIT (Gordon, Flin, & Mearns, 2005) and thereby improve consistency in assessing failures, the naming of and differentiation between codes was carefully reviewed prior to its use in Study 1. Concerns were identified that could have contributed to low inter-rater reliability. As a consequence, the following modifications were made to the format and use of HFIT:

- **Naming of codes.** Table 1 provides a list of the HFIT codes pertaining to each of the major categories. Several of the top-level codes were renamed to better reflect the questions used in HFIT. For example, *Communication* appears twice, both as an *Action Error* and again as an *Organisational Threat*. *Communication Errors* in the *Action Error* category was therefore renamed *Information*, as most of the questions concern the quality of information supplied. The code for *Communication* then refers only to the questions on flawed communication processes listed in *Organisational Threats*. *Plant, Parts, Tools, and Equipment* was renamed *Design & Maintenance*, as plant design and maintenance condition are the two principal lines of questioning, and to better distinguish this code from *Human-Machine Interfacing*, which includes questions that are mainly concerned with alarms. The generic code *Quality* was clarified by considering it as *Work Quality* in order to focus on this important source of maintenance failures.

Table 1. Major categories, and individual, group, and organisational level codes in HFIT.

Action Errors	Situation Awareness	Organisational Threats
Omission	Loss of **Attention**	Inadequate **Procedures**
Timing errors	**Detection** failures	Inadequate **Work Preparation**
Sequence errors	**Memory** faults	**Job Factors**
Selection mistakes	**Interpretation** errors	**Person Factors**
Work Quality	**Decision-making** errors	Lack of **Competency & Training**
Incorrect **Information**	Mistaken **Assumption**	Faulty **Communication**
Procedure Violations	Flawed **Execution**	**Teamwork** issues
		Insufficient **Supervision**
		Organisational Culture
		Difficulties with the **Work Environment**
		Human-machine interfacing **(HMI)** flaws
		Inadequate attention to **Design & Maintenance**
		Difficulties in accessing **Policies & Standards**

N.B. HFIT code names are highlighted in bold.

- **Interpretation of codes.** The code *Organisational/Safety Culture* included a broad range of organisational dimensions, such as the existence of management commitment, a reporting culture, and improper incentives, much of which would be difficult to identify unambiguously in a brief interview. Also included in this code were questions concerning organisational learning. In consideration of the prominence in the literature of this construct with respect to organisational outcomes, *Organisational Culture* refers to flaws in organisational learning in the incident. The code *Procedures, Standards, and Policies* refers generically to management documents, but also includes procedures, which has a separate code. Therefore, in considering the importance of standards and technical drawings to a technology-intensive operation, this code applies to insufficient technical documentation. All failures attributed to procedures are included in the *Procedures* code.
- **Overlap between codes.** Despite the conceptual distinctions between codes, there remained overlaps between the sub-factor questions in several of the

codes. This could lead to variability in attributing the event to one factor over another. For example, there is conceptual overlap between the categories of *Omissions* and *Memory*, and *Selection* and *Decision-making*. As a result, some overlap in coding was anticipated. Further refinements to the instrument resulting from experience with using it for this study are discussed in Section 4.4.1.

Despite these modifications, there may still be variability in coding due to lack of clarity in the descriptions of events. An understanding of plant engineering and maintenance activities was needed to resolve some of the ambiguity in the event descriptions and the causes attributed to the incidents in the reports. Industrial failures generally involve multiple failure modes contributing to the malfunction of materials and components (Antonovsky, 2006), resulting in the potential for variability in assigning one or more appropriate codes to an event. As the company personnel reporting failures in First Priority were generally not versed in human factors theory, the imprecise use of terms reduced the reliability of the coding process.

4.2.3 Procedure

Entries in the First Priority database for the year 2007 were examined to identify maintenance failures with one or more human factors contributing to the event. These were found in the category *Incidents - Lost Production/Asset Damage*. The incident description pertaining to each event was examined to determine if a failure of a maintenance process was specified or implied. For each maintenance-related incident, the entire data record was examined to determine if one or more human factors were implicated as a contributing factor to the failure. As an example of a maintenance-related failure, First Priority Report Event 07080046 described an LNG hot water header that failed to open due to a faulty pilot valve. It was found in the subsequent investigation that maintenance technicians were unaware of the reason for pumps tripping, that operating documents relating to the relief valve were not easily accessible, and that work procedures had not been followed.

The data for incident entries are recorded in two formats:

- Database fields for direct entry of information. These fields consist of *Event Details, Investigation Findings, Immediate Cause, Root Causes,* and *Key Learnings.* These are fields for free entry of information relating to the incident.
- File attachments containing text information generated by the personnel involved and in the case of more serious incidents, company investigation reports. This includes scanned versions of the Incident/Hazard Report form used by the company to record the details of incidents. On the incident recording forms, the field pertaining to the causes includes tick boxes for a list of 38 possible causes, such as 'Inattention/poor judgements/decision making'. These include both technical and human factors categories, though no guidance is provided as to the interpretation of the human factors listed.

Both formats often contained information on the factors relating to the incident, and therefore all entries and attachments were examined. The wording used in each entry was taken as the basis for assigning codes according to the taxonomy in the revised form of HFIT, with as little interpretation of the wording as possible. This was to leave the interpretation of events to those involved and thereby reduce the influence of bias on the part of the coder. Each incident that had at least one identifiable human factor as a contributing cause was recorded on a spreadsheet with demographic details concerning the identification number, date, location, facility type, and work category (i.e. instrumentation/electrical vs. mechanical).

4.3 Results

4.3.1 First Priority incident data

The total number of Asset Damage/Lost Production incident reports analysed from the First Priority database in 2007 was N=1821. The number that were identified from their event description as relating to maintenance work was N=397 (21.8%). The remainder primarily referred to accidental damage or described failures caused by operations personnel. Of the maintenance-related reports, 61.6% related to mechanical maintenance work and 38.4% related to instrumentation/electrical maintenance work. Among these reports, n=194 (48.9%) were found to specify one or more human factors, as defined by HFIT, as contributing to the failure.

Table 2. Code frequencies for incidents reported in First Priority in 2007.

Category	HFIT Code	FPSO[a]	Gas Platform	Process	Vessel	Total
Action Errors	*Omission*	1	0	4	1	6
	Timing	1	2	1	0	4
	Sequence	0	1	0	0	1
	Work Quality	8	7	4	3	22
	Selection	7	7	8	2	24
	Information	2	7	7	1	17
	Violation	12	9	22	2	45
Situation Awareness	*Attention Failure*	6	10	11	1	28
	Detection	10	18	4	3	35
	Memory	1	1	1	0	3
	Interpretation	1	0	5	0	6
	Decision-making	9	10	13	2	34
	Assumptions	0	5	15	1	21
	Response Execution	1	0	1	1	3
Organisational Threats	*Procedures*	5	8	13	4	30
	Planning & Prep.	5	8	12	2	27
	Job Factors	0	1	3	1	5
	Person Factors	0	0	0	0	0
	Skills/Training	5	4	8	3	20
	Communication	0	8	8	1	17
	Teamwork	1	2	2	0	5
	Supervision	3	5	7	1	16
	Org. Culture	1	5	2	0	8
	Environment	4	2	0	1	7
	Human/Systems Int.	3	11	8	0	22
	Design & Maint.	15	15	7	3	40
	Policies & Standards	3	1	0	0	4
Total		104	147	166	33	450

[a] FPSO= Floating Production, Storage, and Offloading vessel

HFIT coding was conducted on all 194 cases of maintenance failure that had some reference to human factors as a contributing cause. The remainder may have had contributing human factors as well, but these were either not recognised by the incident investigators as contributors to the failure, or were not reported due to sensitivity concerning the issues involved. This sensitivity may relate to a reluctance to reveal knowledge of personal actions in production failures or to ascribe blame to workmates. Table 2 shows the frequency of HFIT codes, arranged by facility type, identified in the maintenance-related incidents recorded in the First Priority database in 2007 in which at least one human factor was mentioned. A mean of 2.32 codes per incident was observed in the First Priority reports. A histogram of the frequencies of codes reported in incident reports is show in Figure 3.

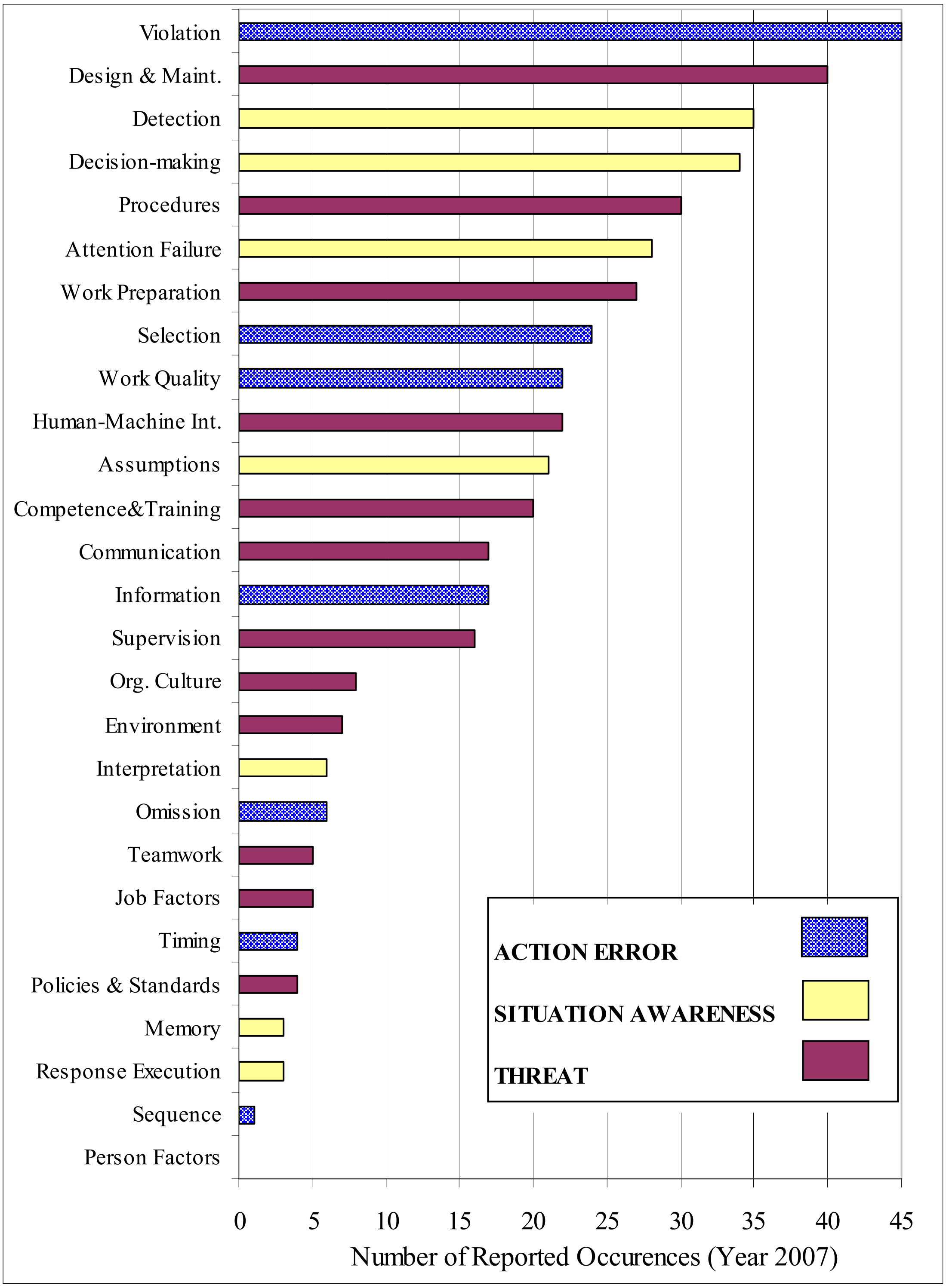

Figure 3. Histogram of the failure codes recorded in First Priority incident reports.

4.3.2 Examples of reports

A discontinuity in the slope can be observed in the histogram of failure code frequencies (Figure 3) between *Decision-making* (fourth most frequent code) and *Procedures* (fifth most frequent code), indicating a visibly higher reporting rate for the first four codes. A second discontinuity was observed indicating low reporting rates of the 12 least-reported contributors. The following are detailed examples from the four most frequent codes.

#1. *Violation*

In one incident, a fault occurred during software testing. The testing, namely entering a 'fire detected' signal, required disabling several data points beforehand, one of which was not disabled. When the software test was executed, the Hot Oil Circulation pump and the Hot Oil Heater were accidentally tripped. A condition of testing the system was that it be 'peer-checked,' which was not done. In the incident report, the *Immediate Cause* was recorded as 'Inattention/poor judgements/decision making,' which was chosen from a list of 38 possible causes. The *Root Cause,* which is entered as free text, was recorded as 'Procedures not followed.' No further details as to the workplace situation, prevailing circumstances, or motivations for the failure to check the state of the system before testing were recorded.
(First Priority Report Event 07110152)

#2. *Design & Maintenance*

A vent valve that was designed to vent high pressure gas failed to open when operated. This valve prevents gas bleeding past another valve from collecting in sufficient quantity in the turbine casing to cause an explosion. A similar fault had occurred 6 months previously, which had been attributed to a faulty operating coil. However, the correct replacement was not available at the time and another valve was substituted, which was not suitable for the application. In the incident report, the *Immediate Cause* was recorded as 'Inadequate guards, barriers, or safety device,' which was chosen from a list of 38 possible causes. The *Root Cause* was recorded as 'Incorrect spares held in stock.' No *Key Learnings* were recorded in First Priority in the section provided. In addition, the decision-making related to using an incorrect spare and not determining the potential danger was also not recorded.
(First Priority Report Event 07020075).

#3. *Detection*

An investigation of a compressor trip revealed that wiring circuits in the control / start panel had abraded through the insulation and electrically shorted causing an electrical failure. In addition, the enclosure was found to be corroded, the rail supporting the electrical equipment had vibrated loose, and the back plate was held on with only two screws causing an elevated level of vibration in the control panel. A potential existed for sparks and an explosion, with the potential damage assessed in the category A$ 100K-A$ 1M. In the incident report, the *Immediate Cause* selected from the list of causes was 'Damaged/ tools/equipment.' The *Root Cause* was recorded as 'Risk not adequately assessed / Regular inspection against performance criteria was poor - vibration effect on associated equipment was not adequately considered when developing inspection criteria.' No *Key Learnings* were recorded in the section provided in First Priority. In addition, there was no indication of what factors contributed to the equipment reaching this state of maintenance or why there had been a failure to detect the deteriorating condition of the electrical cabinet. (First Priority Report Event 07070017)

#4. *Decision-making*

In a mechanical maintenance incident hand holes were being drilled from the top and bottom. The maintenance technicians on the bottom level, who were cutting out coupons of metal and working their way around a column, drilled the wrong holes and did not realise that the nozzle they were drilling into was not marked on their drawing. The original First Priority report indicated that the *Immediate Cause* selected from the list of causes was 'Inattention/Poor judgement/ Decision-making.' The *Root Cause* was recorded as 'Lack of communication between ops [Operations staff] and KEQ [contractor].' In addition to decision-making and the other contributors mentioned in the First Priority entry, a follow-up investigation report mentioned additional contributing factors including a lack of written or verbal instructions to the maintenance technicians, procedures being available for similar activities but not this activity, and required identification checks on the location of relevant pipe-work not being carried out. (First Priority Report Event 07050028)

4.3.3 Analyses

Statistical analyses of the incident data were conducted to determine if the observed differences in occurrence of codes were statistically significant or no better than randomly distributed. As the data were not normally distributed, and the factors were not independent of each other, non-parametric methods for related variables were used (Siegel, 1956). For dichotomous responses with k-related factors, Cochran's Q test can be used to determine if observed differences between codes are statistically significant. In this study, codes (k=27) were tested for each of the incidents examined (n=194). For this dataset, Cochran's Q = 291.36, df=26, (p<.001, α=.05), indicating that a significant difference in the frequency of reported factors exists in the data.

The Cochran's Q test however does not indicate where the significant difference occurs in the frequency data (Allen & Bennett, 2008). To determine where there were significant differences between reported factors, pair-wise McNemar Tests were conducted. The McNemar Test of Change is a non-parametric test for significance in the case of two related samples consisting of dichotomous data (Siegel, 1956). A discontinuity in the slope of the code histogram (Figure 3) was observed between the 4th and 5th most frequent codes, and so the five most-frequently occurring codes were subjected to McNemar Tests. The test results (Table 3) indicated that differences in reported frequency between closely-ranked codes were not significant, but that there was a trend towards a significant difference between codes with a greater difference in rank order (e.g., 1st and 5th most frequent).

Table 3. Pairwise McNemar Tests among the five most-frequently reported codes.

Codes Compared	Exact Significance two-tailed (p)	Significance (α=.05)
Violations(#1) vs. Design & Maintenance (#2)	.657	*ns*
Design & Maintenance (#2) vs. Detection (#3)	.620	*ns*
Detection (#3) vs. Decision-making (#4)	1.000	*ns*
Decision-making (#4) vs. Procedures (#5)	.651	*ns*
Violation (#1) vs. Procedures (#5)	.092	Trend

4.4 Discussion

4.4.1 Objective 1: Selecting and refining a methodology for identifying human factors in maintenance failures

Based on the theoretical framework described in Section 4.1.1, and supported by taxonomy appropriate to the petroleum industry, the Human Factors Investigation Tool (HFIT) was selected as the method for identifying those human factors that are the main contributors to maintenance-related failures in petroleum operations. By adapting the terminology used and modifying the format of HFIT, a methodology has been demonstrated for determining the human factors which recur most frequently in company-based failure reports. The results (Figure 3) indicated that a differentiation between the frequencies of factors could be obtained. In addition, the Cochran's Q test indicated that the differences observed between the frequencies of codes were significant. The McNemar test however, indicated that the differences observed between the four most-frequent codes were non-significant.

4.4.2 Objective 2: Identifying the most frequent human factors in First Priority failure data

The most-frequently reported code in the First Priority data was that of *Violation,* occurring in 23.2% of the incidents. Violations of procedures were frequently selected from the list of causes in the *Immediate Causes* section of the First Priority incident record, though as in the example provided, supporting information for this assessment was often not provided. The prominence of this code accords with the finding of the National Transport Safety Board in the US (Collier, 2004) that 76.5% of adverse events in aviation related to maintenance involved 'failure to follow procedures.' The frequency of occurrence may have been lower in the present study because maintenance procedures are more extensive in the aviation industry (Hobbs & Williamson, 2003) and their enforcement more rigorous than in the petroleum industry.

The next most prominent code, *Design & Maintenance*, is associated with the aspects of equipment design and component quality that have resulted in maintenance failures. The prominence of this item as the second most frequent code in First Priority reports reinforces the view that original designs and the availability of quality spares are recognised as an influence on the ability to maintain plant

(Tjiparuro & Thompson, 2004; Wani & Gandhi, 1999) and in turn ensure plant reliability. A focus on technical factors was discussed by Bea (1998) who considered that design engineers do not tend to concern themselves with the human support systems required for engineered systems. It may also indicate that the technical components of failure were more readily recognised in investigations than most of the other human factors examined. As in the *Design & Maintenance* example provided above, most of the initial First Priority incident reports and the subsequent investigation reports provided extensive detail concerning the technical aspects of the fault, but only allusions to human factors, with little actual investigation of the circumstances surrounding the execution of maintenance activities (refer to Holmgren, 2005).

Detection, the third most-frequent code, represents incidents in which the investigator or reporter deemed with hindsight, that there existed information at the time of the incident that the maintenance crews could have seen, but did not notice. The prominence of this code agrees with the research conducted into loss of situation awareness, particularly with flight crews (O'Leary, 2002) and air traffic control (Pounds & Isaac, 2003; Straeter & Kirwan, 2002). As Dekker (2006) commented in his description of hindsight bias, 'failure to detect' (i.e. loss of situation awareness) and 'poor decision-making' are forms of human error that are attributed in hindsight when determining 'what people should have noticed' and 'what people should have done'. As expected with hindsight bias, the example above illustrated that First Priority entries tended to attribute incidents to individuals failing to observe faults. At the same time, entries often neglected to identify the failure of organisational systems to put measures in place to check for evolving failures. This in itself was an important finding of Study 1.

A consequence of a focus on detection failures is the assumption that subsequent decisions were flawed as a result of loss of situation awareness. Thus, the fourth most-frequent code reported in the First Priority database was *Decision-making.* An attribution of poor decision-making as a failure cause will be expected where third parties, such as supervisors, are responsible for assigning the causes of a failure, as often occurs with reports in First Priority. As with detection, Dekker (2005) considered that any attempt in hindsight to attribute erroneous or inappropriate decisions to the people involved with a failure would be flawed by Hindsight Bias. He invoked the Local Rationality Principle, namely, that at the time of an incident, the decisions of the participants appear to be rational to them. In the example above, there was an expectation in retrospect that the maintenance technicians should have made better decisions. This conclusion was reached despite the subsequent report that technicians were not given appropriate written or verbal instructions, there was no procedure for the activity, and that a failure to communicate was acknowledged as a root cause.

4.4.3 Value of First Priority data

Study 1 relied on an analysis of past adverse incidents to develop an understanding of the role of human factors in failures. Information was gained by extracting maintenance-related incidents with at least one human factor cause mentioned. Analysing incident reports in First Priority was intended as a preliminary investigation of existing data on company failures. The data was available electronically, and therefore easily accessed, and provided a large sample population of incidents. The investigations conducted and reports filed at the time of the failure would have the advantage of recency over descriptions of events and contributing factors collected later. On the basis of associated demographic data, First Priority also provided a means of comparing the relative frequency of human factors in failures occurring across different facility types (Table 2). Among the three most frequent codes discussed (Section 4.3), *Violation* was proportionally highest in the Process Plant, *Design & Maintenance* was proportionally highest on the FPSOs, and *Detection* was proportionally highest on the gas platforms. The differences in *Design & Maintenance* may relate to the process of constructing an FPSO by converting a ship to an oil production plant. The reasons for relatively more detection errors on gas platforms and violations in the Process Plant were not clear from the reports, but may be an indicator of different workplace designs (e.g., offshore vs. onshore), and consequently different reliability climates.

Examination of the database provided an opportunity to trial HFIT as a method for investigating incidents retrospectively, and in situations in which the ability to obtain additional information is limited. It was found that some reports explored organisational contributors in detail, while other reports only attributed failures to

Violations and *Detection* errors. By examining the data and reports in First Priority, it was also possible to understand the limitations in company failure investigations, and determine how they could be improved in order to better assess the contribution of human factors.

4.4.4 Biases in First Priority data

The information available from reports filed within the incident recording database was found to be rich in event descriptions, but poor in contextual and motivational analysis. As noted in the examples, information concerning organisational contributors to the incidents was needed to understand why decisions and actions were taken. Understanding underlying motivators might have explained, for example, why an unsuitable substitute component was used in the example given earlier involving a *Design & Maintenance* incident.

Reports of organisational and personal factors associated with failures can also be expected to have a degree of bias, depending on how the person examining the incident deconstructs the events in their own mind, and what type of accident model they apply to the circumstances (Dekker, 2006). The root causes ultimately identified will depend on the perspective and mental model of the investigator. Therefore any factors that do not fit with a participant's reconstruction of events may be difficult to elicit. The data in First Priority suffered from some of the faults which were also encountered by Pyy (2001) in his examination of maintenance history reports at the Olkiluoto NPP in Finland. He described flaws found in the data relating to subjective bias, lack of human factors categories in reports, a tendency towards better reporting of specific types of faults, and variability in the quality of reporting depending on the area of the plant involved. Similarly in Study 1, although 12 incidents involving violations were reported in FPSOs, no incidents involving communication were reported. From an organisational perspective this seems unlikely. At the same time, gas platforms and the Process Plant reported eight incidents each involving *Communication*, supporting Pyy's contention that operational areas tend to report specific types of failures. Similarly, in the First Priority reports, categories available to reporters were often poorly differentiated, such as the single category of *Inattention/Poor judgement/ Decision-making.* This might have led to higher reporting of certain categories, such as *Violation,* and lower reporting of underlying factors. For this reason, in order to reveal the human factors influence on failures, direct examination of incidents by an investigator with human factors expertise is likely to be more effective.

4.5 Summary and Conclusions

The objectives of the first phase of Study 1 were to select and refine a methodology for determining the human factors involved in petroleum industry failures, and apply the method to determining the human factors that most frequently contributed to maintenance-related failures. Using HFIT to analyse a company-wide incident database, Study 1 provided a large quantity of data that supported these objectives. In total, 397 maintenance-related adverse events reported in 2007 in the company's production facilities were identified, with a description of circumstances surrounding the associated maintenance activities. At least one human factor was found in reports from 48.9% of these incidents, indicating that at least this proportion had an identifiable human factors influence. However, the quality of the data provided did not support a comprehensive analysis of the human factors contributors to maintenance failures. This conclusion was based on the findings in this chapter, namely:

- the lack of investigative detail, particularly in the incident report sections entitled *Immediate Causes* and *Root Causes*;
- a tendency for reports to focus on technical causes, rather than underlying organisational contributors;
- biases identified in reporting of specific factors on particular facilities;

In conclusion, Study 1 provided many indicators, from the perspective of company personnel, of the possible role of human factors in maintenance-related failures. However, a more accurate means of determining the frequency of occurrence of human factors in failures was required, including greater consistency in assessing each of the factors which contributed to a specific incident. In the next chapter, Study 2 provides a more rigorous and detailed investigation of the human factors contributing to maintenance-related failures within the company's operations.

5.0 Study 2: Identifying Human Factors through Failure Interviews

5.1 Introduction

5.1.1 Background and justification for Study 2

In Chapter 4, the selection and refinement of a methodology was reported for determining the human factors that most-frequently contributed to maintenance-related failures in petroleum industry operations. The methodology was then applied to a representative sample of maintenance-related Lost Production/Asset Damage incidents reported in a 12-month period, obtained by examining First Priority, the company-wide database of adverse incidents. An investigation of the First Priority incident reports provided substantial data concerning the types of failures that result from maintenance activities in a petroleum operation. A benefit of exploring the database was that it provided preliminary data concerning the human factors regarded by company investigators as the immediate and root causes of these failures. In addition, it provided comprehensive demographic data relating to the failures, including the work category (mechanical or instrumentation/electrical), facility type (FPSOs, gas platforms, or Process Plant) and work area (facility or process plant area). However, as described in Section 4.5 the quality of data was found to be impaired by a lack of human factors content, inconsistencies in reporting between individuals on different facilities, and biases, particularly towards reporting violations and human error, in assessing the causative factors involved.

Dekker (2006) cautioned against taking accident history out of context in order to reconstruct the causes in hindsight, in a process he termed ‘cherry-picking’ through an accident sequence. He argued that there is a tendency to pull together fragments of information relating to an event and then to construct causality around it. The high frequency of First Priority reports naming violations and human error (e.g. *Detection* and *Decision-making*) as the cause tended to support his contention. In recognition of the possible flaws in company incident reports, greater depth of human factors analysis was required to provide the necessary background information required for this research. Consequently, an alternative source of data concerning maintenance failure history was sought. This was the basis for conducting Study 2.

In order to avoid the flaws in Study 1 described above, incidents needed to be discussed directly with the participants involved, using a standardised format to maintain the consistency of analyses between the incidents, and a consistent interpretation of the contributing factors. To accomplish this, Patton (2002) recommended using a Standardized Open-Ended Interview format, namely one in which the order and structure of questions is consistent between interviews, but interviewees are also allowed to express their perspective. Using the questions in HFIT, the interviewee's perception of events, which Patton regards as "meaningful, knowable, and able to be made explicit" (p. 341), could be reduced to a dichotomous choice between *Present* or *Not present* for each possible factor. At the same time, the richness in the interviewee's understanding of how a particular factor contributed to the failure could also be recorded. In this way, a structured interview methodology could provide consistency between interviews and reduce the potential for bias on the part of the interviewer, while observing Patton's contention that, "The fundamental principle of qualitative interviewing is to provide a framework within which respondents can express *their own* understandings in their own terms" (p. 348). At the same time, the use of HFIT provided a structure to ensure that a comprehensive range of possible human factors contributors to failures was examined.

5.1.2 Study 2 objective

Based on the use of structured interviews with maintenance personnel, the principal objective of Study 2 was to determine the human factors that contributed most-frequently to maintenance-related failures in petroleum maintenance operations. Detailed structured interviews using HFIT were considered less likely to suffer from the data collection flaws that were found in the First Priority reports examined in Study 1.

5.2 Method

5.2.1 Participants

Experienced instrumentation/electrical and mechanical maintenance personnel (N=38) participated in the interviews for Study 2. All participants were over the age of 18 years old. The demographic distribution of participants involved in Study 2 is provided in Table 4. Participants included maintenance technicians, coordinator/

planners, and supervisors. Maintenance personnel generally fall into two distinct categories, namely facility-based Core Crews and fly-in/fly-out Major Maintenance crews responsible for assisting during shutdowns. Core Crews are employed at a particular facility, either on a full-time basis in the case of the on-shore Process Plant or on a fly-in/fly-out roster on the off-shore facilities. Major Maintenance crews are based at the company's headquarters and are sent to off-shore facilities when large maintenance projects or plant shutdowns are undertaken.

Table 4. Distribution of participants in Study 2 interviews.

Demographic	Type of Interviewee	Number of Interviews	% of Interviews	Organisational Data (%) [a]
Position	Maintenance Technician	21	55.3	81.0
	Maintenance Coordinator	11	28.9	13.9
	Maintenance Supervisor	6	15.8	5.1
Workgroup Type	Core Crew (Off-shore)	12	31.6	60.2
	Core Crew (Process Plant)	11	28.9	33.7
	Major Maintenance /Shutdown	15	39.5	6.0
Gender	Male	38	100	97
	Female	0	0	3

[a] Based on overall operational staffing levels

5.2.2 Measure: HFIT

HFIT (Gordon, 2001), as adapted and described in Section 4.2.2, was used to gather human factors information in the structured interviews conducted with participants. The modified codes and the sub-factors under-lying the main codes were arranged into an interview template (Appendix A). Each page provided tick boxes to record the 'Yes' or 'No' responses from the interviewee to interview questions concerning the top level HFIT code and the under-lying sub-factors. The format also provided space for recording comments made by the interviewee relating to the code under discussion. Comments were valuable as background information to support the interviewer in interpreting the dichotomous responses received from the interviewee.

5.2.3 Procedure

5.2.3.1 Interviews

Approval for the research was granted (Approval Number HR 147/2007) by the Human Research Ethics Committee of Curtin University of Technology (Appendix B). For Study 2, a cross-section of maintenance personnel was obtained by recruiting interviewees from the Process Plant, off-shore Core Crews from one of the FPSOs, and from the Major Maintenance crews. Names of maintenance personnel were suggested by team leaders. They were then contacted by telephone or e-mail in order to describe the reasons for the interview and the procedure to be followed, and invite them to participate. Most of the maintenance personnel contacted agreed to be interviewed, with six declining due to scheduling difficulties. An Information Sheet (Appendix C) describing the purpose of the research and the procedure for the interview was sent to potential participants by e-mail. In the letter they were advised that the interview was voluntary, and that the company would not know who had participated. The information sheet also informed them that the interview would be recorded, but would be de-identified, and that raw recordings would not be made available to the company. Only one interviewee refused to be recorded, but still agreed to proceed with the interview, and this interview was included in the data. All interviewees were advised that they could withdraw from participating at any stage in the process, though no one elected to do this.

Interviews were conducted from February to July 2008. Personnel who agreed to be interviewed were invited to a one-to-one interview session. The interviewee was asked to recall a failure with which they were personally involved, preferably in the past two years. This served to eliminate selection bias on the part of the interviewer. A failure was defined as any type of maintenance activity that did not produce the anticipated outcome, such as:

- a maintenance activity that failed to correct the existing problem,
- activities carried out that caused a new problem, which resulted in a production failure afterwards, or
- a maintenance activity that did not proceed as planned.

The HFIT template (Appendix A) was used to structure the interviews. This consisted of a large number of questions drawn from the original version of HFIT

(Gordon, 2001). In the time available for an interview, it was not possible to ask all of the questions. Therefore, they provided a guide for questioning the interviewee about whether the code under discussion was a contributor or not. The questions were also useful in eliciting supporting information. The interpretation of the meaning of the codes adopted in Study 1 was continued in Study 2.

Each interview was recorded, for review of the responses and to obtain verbatim quotes. Recordings were converted to a compressed file format (i.e., MP3) and stored confidentially on a computer. Interviews lasted between 30 minutes and 1½ hours.

5.2.3.2 Analyses

The recordings were analysed a short time after the interview to ensure recency in interpreting each interview. This included selecting the code and sub-factor, and recording relevant comments on the interview sheet. A second coder (the research supervisor), dual-coded a random sample of interviews. Clarification of items was resolved through this process. All interviews were also re-coded at the end of the interview phase to ensure that interpretation was consistent across all interviews.

In addition, each incident was assigned a severity rating. The criteria applied for assessing severity, derived from the International Standard "Petroleum, petrochemical and natural gas industries-Collection and exchange of reliability and maintenance data for equipment" (International Standards Organization, 2006b, Table C.1) were as follows:

- *Minor*- the incident resulted in organisational costs (< $50,000) but did not result in lost production or provide the potential for a future stoppage.
- *Moderate*- the incident resulted in a number of hours of lost production, additional repair costs ($50,000-250,000) or a minor injury, or created the potential for a significant stoppage or injury.
- *Severe*- the incident resulted in a number of days of lost production, additional repair costs (>$250,000), or serious injuries, or created the potential for major damage to plant, such as an explosion. (p. 134)

5.3 Results

5.3.1 Interview incident data

Table 5 shows the classification of interviews (N=38) by work category, production product, and severity of the consequences. The incidents investigated occurred between Jan 1998 and July 2008 with the majority (58%) occurring in the previous 12 months. At one extreme were relatively minor incidents, such as one involving delivery of incorrect regulators due to problems with the electronic work order system, and which resulted in a short delay to the maintenance task. At the other extreme were major incidents such as a faulty repair to a davit that was incorrectly specified, severely injuring 13 people, and a poorly organised shutdown that resulted in $50,000 of additional maintenance costs, and $3 million in lost production. The most severe incident resulted in a situation in which the potential for an explosion existed, the interviewee commenting, "We could have lost the gas plant."

Table 5. Classification of incidents reported in the Study 2 interviews

Demographic	Incident	Number of Interviews	% of Interviews	Organisational Data (%)
Work Category	Instrumentation/Electrical	15	39.5	38.4[a]
	Mechanical	23	60.5	61.6[a]
Type of Production	Gas (Platforms and Process Plant)	17	44.7	62.1[a]
	Oil (FPSOs)	21	55.3	37.9[a]
Severity of Consequences	Minor	9	23.7	45.1[b]
	Moderate	16	42.1	35.3[b]
	Severe	13	34.2	19.6[b]

[a] Based on entries in First Priority for maintenance-related incidents (Year 2007)
[b] Based on entries in First Priority for maintenance incidents with a reported human factor (Year 2007)

5.3.1.1 Failure code frequency

The frequency data for HFIT codes and severity data attributed to failures in the interviews with Major Maintenance crew, Process Plant Core Crew, and the FPSO Core Crew are provided in Appendix D. Multiple contributors to each failure were reported in the interviews (Table 6), with the mean number of reported factors, k_{mean}= 9.47 (Range= 6 to 15, SD=2.25). Graphical comparisons of the data in

Table 6 indicated no apparent association between facility types and the frequency of codes recorded or the severity ratings of the incidents.

Table 6. Number of reported codes per incident and severity rating, arranged by facility type.

FPSO			Gas Platform			Process Plant		
Interview Code	Severity	No. of Codes	Interview Code	Severity	No. of Codes	Interview Code	Severity	No. of Codes
MMO1	Med	7	MMG1	Low	11	GPP1	Med	12
MMO2	Med	9	MMG2	Med	10	GPP 2	High	7
MMO3	Med	9	MMG3	Med	6	GPP 3	High	8
MMO4	Med	6	MMG4	High	9	GPP 4	High	13
MMO5	High	8	MMG5	High	10	GPP 5	High	13
MMO6	Low	10	CCG1	Low	8	GPP 6	High	9
MMO7	Low	9				GPP 7	Low	9
MMO8	Med	7				GPP 8	Med	15
MMO9	Med	10				GPP 9	High	13
COS1	Low	9				GPP 10	High	9
COS2	Low	12				GPP 11	Med	12
COS3	Med	8						
COS4	High	13						
COS5	Med	7						
COS6	Med	9						
COS7	High	9						
COS8	Med	7						
COS9	Low	10						
COS10	Med	6						
COS11	Low	9						
COS12	High	12						

As an example of multiple factors occurring in a single incident, Interviewee GPP1 reported an incident involving a new turbine bearing that was leaking oil on being brought up to pressure after maintenance. Leaking oil flashed off the overheated bearing, tripping an infra-red detector which then shut down the turbine. The maintenance supervisor reported that the design of the turbine involved two different sized bolts, and using the wrong bolt prevented the cover from sealing, allowing oil to escape (*Design & Maintenance*). In addition, it was "assumed that a big block of metal would sit flat" and that the oil had been leaking from the oilways, and not the cover (*Assumption*). Therefore a decision was made not to check the cover (*Decision-making*). The manufacturer did not supply information concerning the bolts or the final checks needed to be done on the cover (*Procedure*). The procedures also had not been up-dated, with incorrect drawings showing a wrong location of the hole for the rotor (*Policies, Standards, and Procedures)*.

The frequency of major HFIT categories, namely *Action Error, Situation Awareness,* and *Organisational Threat*, reported in the interviews is shown in Table 7. The frequency of these categories were relatively evenly distributed among the different types of facilities, work categories (mechanical and instrumentation/ electrical), and severity ratings. The overall numbers of *Organisational Threats* tended to be high due to the larger number of codes (13 codes) relative to *Action Errors* (7 codes) and *Situation Awareness* (7 codes). The frequency of individual codes, also arranged by facility type, work category, and incident severity is shown in Table 8.

Table 7. Frequency of major HFIT categories arranged by facility type, work category, and severity.

	FPSO	Platform	PP	Instr/Elect.	Mech.	Severe	Mod.	Minor	Total
Action Errors	47	10	25	35	47	29	32	21	82
Situation Awareness	52	14	24	38	52	35	35	20	90
Organisational Threats	111	24	53	79	109	69	73	46	188

Table 8. Frequency of HFIT failure codes arranged by facility type, work category, and severity.

	FPSO	Gas Platform	Process Plant	Instr/ Elect	Mech	Severe	Mod	Minor	Total
Assumption	17	5	8	13	17	11	12	7	30
Design & Maintenance	17	4	6	13	14	12	9	6	27
Communication	17	4	4	12	13	11	7	7	25
Omission	11	2	9	8	14	6	10	6	22
Decision-making	13	3	5	10	11	10	8	3	21
Information	9	2	6	5	12	4	7	6	17
Procedures	7	5	5	4	13	3	10	4	17
Competency	12	1	3	8	8	7	4	5	16
Detection	10	2	3	7	8	6	4	5	15
Plan. & Prep.	9	1	5	6	9	5	5	5	15
Org. Culture	8	1	6	7	8	6	6	3	15
PSP	8	3	4	5	10	5	7	3	15
Job Factors	9	2	3	6	8	6	5	3	14
Timing	8	2	4	6	8	6	6	2	14
Selection	7	2	3	6	6	4	4	4	12
Attention	5	2	5	4	8	4	6	2	12
Supervision	7	0	4	6	5	5	4	2	11
Work Environment	6	1	4	3	8	2	5	4	11
Work Quality	6	2	2	6	4	6	4	0	10
Teamwork	4	1	4	3	6	2	5	2	9
Person Factors	5	0	3	4	4	3	3	2	8
Violation	6	0	1	4	3	3	1	3	7
Memory	3	1	2	0	6	0	3	3	6
HMI	2	1	2	2	3	2	3	0	5
Interpretation	3	0	1	3	1	3	1	0	4
Execution	1	1	0	1	1	1	1	0	2
Sequence	0	0	0	0	0	0	0	0	0

Figure 4 provides a histogram of the distribution of codes in rank order of frequency. Frequencies of reports by facility type are also shown.

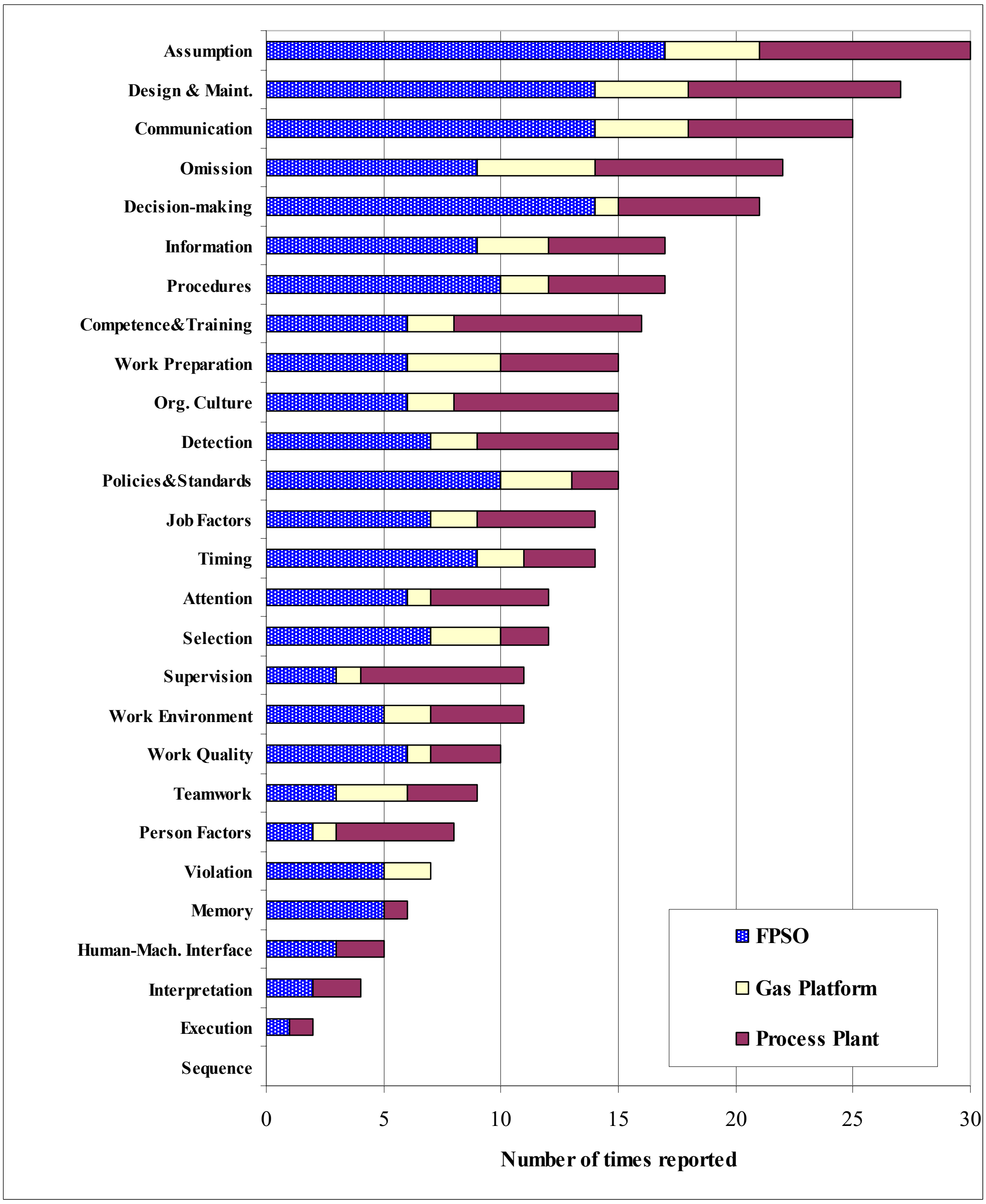

Figure 4. Histogram of the failure codes displayed according to facility types.

Visual interpretation of this data indicated a discontinuity in slope occurred between *Communication* (#3) and *Omission* (#4), with a larger discontinuity between *Decision-making* (#5) and the remaining codes. Based on this, the following is a detailed review of the five most-frequent factors found to be contributors to the failures discussed in the interviews:

#1) ***Assumption.*** Reported in 79% of cases. This item included any failure associated with assumptions made on the part of maintenance technicians or support personnel (e.g. supervisors, planners, supply chain personnel, or vendors). These were cases in which decisions were made based on inaccurate knowledge, and additional information would have avoided a failure.

For example, in a number of cases the correctness of components or procedures to be used was assumed but not verified. In one example, the failure of a transducer required a circuit breaker to be shut off. It was assumed that the breaker could be shut off without affecting other units. However, due to poor labelling of the unit involved, inaccurate drawings, and the fact that "maintenance procedures haven't been addressed" compressors were also switched off causing the entire production stream to shut down. The maintenance technician commented, "The majority of our work is trying to find the information to hand on to the inexperienced guys to make their work task safe, because they don't have that local knowledge." (Interview COS8)

In another example from an interview describing an oil spill from an open valve, the person involved isolated a critical valve and "made the assumption it was working. If you close a valve, you assume it's closed." (Interview COS3).

#2) ***Design & Maintenance.*** Reported in 71% of cases. This item included maintenance difficulties attributed to the design of equipment or components, or difficulties caused by insufficient regular maintenance or a need for condition monitoring. This code was intended to capture failures due to deficiencies in the maintainability of the engineering design or a failure to provide on-going maintenance.

In a serious failure described, a modification to correct a design fault almost caused an explosion on-board an FPSO. The water seal used in a Pressure-Vacuum (PV) breaker was used to isolate hydrocarbon storage tanks from exposure to air. The gauge measuring the level of water in the seal was checked daily. However, due to insufficient maintenance, the gauge was difficult to read. New designs were considered, but never implemented. As a consequence, a maintenance technician decided to modify the gauge in order to alleviate the difficulties with reading it. Part of his modification included an elbow joint which eventually corroded, allowing water to drain from the seal. This released poisonous inert gas from the tank and exposed explosive hydrocarbons in the tank to air. (Interview COS12)

In another example, a steampipe for oxygen removal in an aerator was poorly designed and manufactured, and eventually cracked, shutting down the steam plant. Rather than re-manufacturing the pipe to a higher specification, a welder was flown to the FPSO to repair the crack. The pipe cracked again, this time causing 3-4 days of lost production, and risking damage to a boiler. If accurate drawings had been available, the pipe could have been replaced in 48 hours with a new pipe manufactured on-shore. (Interview COS4)

#3) ***Communication*****.** Reported in 66% of cases. This included any lack of communication or mis-communication between the relevant stakeholders, including maintenance technicians, supervisors, on-shore and off-shore crew, and vendors of equipment and parts.

For example, changes made to a lip sealing arrangement by a vendor in conjunction with the Engineering Department were not communicated to the shutdown team installing the seal. The changes were also not communicated via the on-line Bill of Materials parts list. The interviewee commented that communicating the change could have been as simple as marking the change of seal on the machine concerned. As the shutdown was re-scheduled from mid-week to the weekend, obtaining the correct seal required helicopter transport, at a total excess cost of $3 million in transport and lost production. (Interview MMG4)

In another example, scaffolding was required for a task, but a lack of communication between planners and maintenance technicians meant that the need for scaffolding was not discussed, and not included in the work plan. A mechanical fitter reported that a job that should have taken a “couple of days, ended up taking a week, [due to] miscommunication between [our company's] resource estimators and [the contracting company]." (Interview GPP7)

#4) *Omission*: Reported in 58% of cases. If an integral task or step in the work process was not carried out, and this was associated with the failure, an omission was considered to have occurred. Failure to check work done or parts used was considered an omission, if this was a normal step in the particular activity.

In an example involving a failure costing "millions of dollars," a modification to a gas turbine bearing meant that a hole in an oil gallery should have been plugged, but this step was omitted. (Interview GPP9)

#5) *Decision-making*. Reported in 55% of cases. This item concerned any decision that was made, which subsequent events showed to be a flawed decision. This included incorrect and inappropriate solutions to problems, or failure to consider relevant factors during the decision-making process.

In an example of poor decision-making, the seal on a pump caught fire. A decision was made to replace the seal without investigating the cause of the failure. The seal was replaced twice at a cost of $20,000 per seal, before it was realised that flow in the cooling lines was insufficient. Warning signals had indicated that flow rates might have been inadequate, but this was not checked. (Interview GPP5)

The relative occurrence of the codes demonstrated a high degree of consistency between the different types of production facility (Figure 4). Notable exceptions to this were:

- *Competence & Training, Organisational Culture,* and *Supervision* appeared to be proportionally higher at the Process Plant, which, according to the opinion of several interviewees, may have been due to the less-experienced workforce there.
- *Work Preparation* and *Policies & Standards*, which refers to the availability of standards and technical drawings, were reported more frequently on the

gas platforms and FPSOs. This may relate to the constraints of working off-shore, including greater difficulty in accessing information and communicating with other personnel.

- *Decision-making* was reported less frequently in failures on gas platforms, while *Omissions* were less of an issue on FPSOs. Typically, gas platforms are larger scale operations with more personnel present on-board compared to FPSOs.

5.3.2 Statistical analysis of interview data

Statistical analyses were conducted on the interview data to determine if the observed differences in occurrence of codes were statistically significant or no better than randomly distributed. As the data were not normally distributed, and the factors were not independent of each other, non-parametric methods for related variables were used. For dichotomous responses with k-related factors, Cochran's Q Test can be used to determine if observed occurrences are randomly distributed (Siegel, 1956). In this study, codes (k=27) were tested for each of the incidents examined (N=38). For this dataset, Q =126.13, df=26, p<.001, α=.05, indicating that a significant difference in the frequency of reported factors exists in the interview data.

The Cochran's Q Test however does not indicate where the significant difference occurs (Allen & Bennett, 2008). To determine if significant differences existed between reported factors, pair-wise McNemar Tests were conducted. The McNemar Test of Change is a non-parametric test for significance in the case of two related samples consisting of dichotomous data (Siegel, 1956). A discontinuity in the slope of the code histogram (Figure 4) was observed between the 5th and 6th most frequent codes, and so the six most-frequently occurring codes were subjected to McNemar Tests. The test results (Table 9) indicated that differences in reported frequency between adjacent codes (e.g. *Assumption* and *Design & Maintenance,* or *Design & Maintenance* and *Communication*) codes were not significant, though a trend was observed between *Assumptions* and *Information*.

Chi-squared Tests of Contingency were evaluated for each of the HFIT codes against *Work category, Incident severity,* and *Facility type*. For *Work category* (Mechanical vs. Instrumentation/Electrical), only *Human-machine interfacing* returned a significant difference (χ^2=5.74, *df*=1, *p*=.017). Among *Facility types*, *Supervision* (χ^2=11.61, *df*=2 *p*=.003) and *Competency & Training* (χ^2=14.19, *df*=2, *p*=.001) showed significant differences. Across *Severity level*, only *Violation* (χ^2=6.34, *df*=2 *p*=.042) and *Procedures* (χ^2=6.03, *df*=2 *p*=.049) showed significant differences.

Table 9. Pair-wise McNemar Tests among the five most frequently reported codes.

Codes Compared	**Exact Significance two-tailed (*p*)**	**Significance (α=.05)**
Assumption(#1) vs. D & M (#2)	1.00	Not significant
D & M (#2) vs. Communication (#3)	.629	Not significant
Communication (#3) vs. Omission (#4)	.629	Not significant
Omission (#4) vs. Decision-making (#5)	1.00	Not significant
Assumption(#1) vs. Information (#6)	.096	Trend

5.3.3 Sub-factors for the most frequent codes

The three most frequent HFIT codes were examined in detail to identify the most frequent sub-factors contributing to these codes (Table 10).

5.4 Discussion

5.4.1 Human factors in maintenance-related failures

The main objective of Study 2 was to develop a more detailed understanding of the human factors that most-frequently contributed to maintenance-related failures in petroleum operations by using structured interviews with maintenance personnel. Analysis of the ranking of reported codes, using a Cochran's Q Test, demonstrated that the frequencies of the 27 codes did not occur randomly. The five most frequently reported codes were:

#1 *Assumption*

#2 *Design & Maintenance*

#3 *Communication*

#4 *Omission*

#5 *Decision-making*

Table 10. Frequency of sub-factors of the three most-frequent codes, and their occurrence as a percentage of the number of times that the code was reported.

HFIT Code	Sub-factor identified in the interview	No. of reports	% of reports
Assumption	Assumption that correct procedures were being used	11	37
	Assumption that correct parts or systems were being fixed	6	20
	Assumption that equipment and location were correct	5	17
	Assumption that previous tasks were carried out	4	13
Design & Maintenance	The design or structure was inadequate	10	37
	Components or materials were inadequate	8	30
	Insufficient physical or visual access	7	26
	Equipment was overdue for maintenance or CM	6	22
	Design or modification not carried out as intended.	4	15
	Components can be installed in the wrong orientation.	4	15
	Incident was related to use of non-standard equipment	4	15
	Equipment in the incident was not adequately labelled.	3	11
Communication	There was a lack of communication	10	40
	Poor communication between companies	8	32
	Poor communication between or within teams/departments	8	32
	Communication failure between offshore and on-shore personnel	5	20

5.4.2 Assumption

Assumption was the most frequently mentioned factor, reported in 30 of the 38 interviews. A positive response to *Assumption* was often associated with solving maintenance problems without obtaining sufficient information, or without checking the accuracy of presumptions. Tucker and Edmondson (2003) described this process as first-order problem-solving in their analysis of the work of hospital nurses and other front-line workers. They described two heuristics that operate in first-order learning, namely 1) securing just the information or materials needed to continue the work process, and 2) asking for assistance, such as information, from other workers who are socially close rather than those more able to assist. Assumptions in turn preclude second-order problem solving; that is the process of probing into underlying factors that are required for complete and long-term corrections of problems.

Assumptions in solving maintenance problems were reported in several forms, including the assumptions that:

- supplied replacement parts were correct for the application
- previous tasks had been done
- the unit being maintained was similar to units previously worked on
- work on an electrical system would not cause production units to switch off and
- the cause of failure resided in a particular area of a system when in fact the fault was situated elsewhere.

Closely related, was the application of assumed knowledge to decision-making. Faulty assumptions were found to be a factor in most of the cases (81%) associated with flawed decisions. In a number of incidents, this was based on an assumption that the job was less complicated than it proved to be. In others there was an assumption that the planned action would improve the situation rather than make it worse, as in the incident where a full overhaul was planned based on the assumption that spare parts were available. Often these assumptions were based on past experience alone. In discussing a Recognition-Primed Decision model (Lipshitz, Klein, Orasanu, & Salas, 2001), a facet of Naturalistic Decision-making, Caravlaho, dos Santos and Vidal (2005) described the way in which NPP shift supervisors tended to decide on a course of action based on the similarity of the current situation to previous situations. These supervisors did not attempt to identify the most appropriate solution, but rather one which sufficiently accorded with their previous experience. This process inevitably required assumptions concerning the similarity of the problem encountered to previous ones, and the applicability of previous solutions, processes considered typical of Naturalistic Decision-making (Lipshitz, Klein, Orasanu, & Salas, 2001).

In the current study, despite using an interview method, there were difficulties in definitively identifying the cognitive processes that led to the failure in question. In most cases, problem-solving behaviours appeared to mediate between the initial assumptions and the subsequent adverse outcome. For this reason, in a majority of incidents, assumptions could be considered a dimension of problem-solving behaviour, including decision-making, which is central to the problem-solving process. Flawed decision-making was found to occur frequently with assumptions. Other important components of problem-solving also featured in the incidents examined. For example, failure to detect warning signs (*Detection* [#11]) often occurred with *Assumption*, as in the failure of a Condensate Pump on an FPSO. Assumptions were made that vibrations heard originated from a bearing, despite the maintenance technician commenting in the interview, "When putting it [the condensate pump] in, there was that much tension; that should have been a warning sign."

Conversely, in many cases involving assumptions (43%), an intermediary decision-making stage mediating between assumptions and failure did not seem to occur, i.e. the job in question was proceeding along an established path and due to the assumption made, no choice between options appeared to be necessary. Examples included those in which a wrong procedure was specified or a wrong part was supplied, and no attempt was made to confirm its suitability. In most of these cases, when *Decision-making* was not a factor, an *Omission* (of a check on suitability) or *Violation* (of a required checking procedure) was reported. These incidents corresponded to situations which can occur in more regulated and proceduralised industries such as aviation and NPP maintenance. Hobbs and Williamson (2003) found that memory lapses, which they defined as "the omission of an action that the person intended to perform" (p.191), was the greatest contributor (20.1% of occurrences) to adverse aircraft maintenance incidents, while violations were the second greatest contributor (17.2% of occurrences). Pyy (2001) similarly identified omissions in 23.8 % of maintenance failures involving a human action resulting in a fault.

In addition to reflecting problem-solving behaviours, the prevalence of assumptions may also be an emergent property representing underlying organisational factors, such as:

- the difficulty of obtaining information, as demonstrated by the frequent reporting of *Communication* (#3) and *Information* (#7)
- real or perceived time pressures to complete jobs quickly (*Job Factors* #9)
- the increasing technical complexity of maintaining plant and equipment, as evidenced by the prominence of *Design & Maintenance* (#2) issues in failures
- the lack of *Procedures* (#6) for many tasks and the reported difficulties of finding procedures, or the tendency of work orders not to contain procedures, as is the practice in other operations.

The human factors literature tended to examine the role of assumptions in relation to other cognitive processes in the workplace, such as decision-making (Lipshitz, Klein, Orasanu, & Salas, 2001), error-making (Reason & Hobbs, 2003), and problem-solving (Edmondson, 1996), rather than as a distinct construct (e.g. 'assumption-making'). Most literature was concerned with either the observable phenomena on which assumptions impact (e.g., information flow and decision-making) or the outcomes of these processes (e.g., generation of observable solutions to problems). Vogus and Welbourne (2003) commented, in relation to information flow and problem-solving, that high-reliability organisations tend to avoid making assumptions or over-simplifying the situations in which they operate. Reiman, Oedewald and Rollenhagen (2005) considered *methodicalness*, the inverse of making assumptions, as an important component of their Maintenance Core Task model (Section 2.11.2). They describe methodicalness as a process whereby the maintenance technician can justify the reasons for undertaking a particular maintenance activity. Their model highlights the importance of "knowledge creation and problem-solving as being inherent in the maintenance task" (p. 334). Ultimately, the relationship of assumptions to the solution of maintenance problems was demonstrated by their predominance in the interview reports of the current study.

5.4.3 Plant design and maintenance

Design & Maintenance was the second most-frequent code associated with failures, both in the interviews and in incidents reported in First Priority. This item has a strong relationship to engineering, but in turn relates to difficulties encountered by maintenance technicians in conducting their work. This code was reported in 71% of the interviews, of which the majority were inadequacies in the components, design, or materials utilised. The remainder of this category included failures due to:

- inadequate labelling of equipment units or controls
- use of non-standardised equipment
- inadequate maintenance or condition-monitoring.

Attribution of failures to the original design or a lack of on-going maintenance is to be expected in a technically-advanced operation. Taylor (2007) quotes two studies concerning the influence of design on incidents in process plants. In one relating to nuclear reactors, design errors were named as a 'primary cause' in 46% of incidents. In a study of chemical industry incidents, 55% involved design errors. A higher overall result (71%) was obtained in the current study, though no attempt was made to identify a primary cause, as was done in the study quoted by Taylor. Maintenance technicians may also be expected to attribute a greater influence to design than incident investigators, as their tasks require dealing directly with the impact of design flaws on maintenance work.

While some elements of plant design are principally engineering issues, the ability of maintenance technicians to interact easily and dependably with the equipment on which they work is an important dimension of a human factors approach to improving overall plant performance. Therefore, some elements of this factor bear on technical issues, such as the adequacy of components or materials, while others such as labelling, access, and use of non-standardised equipment impact directly on maintenance technicians' ability to complete their tasks. In the opinion of Reason and Hobbs (2003), many maintenance errors are related to design of equipment and often are due to a lack of concern for the work of maintainers. They suggest a focus on six design principles:

1. "Components should be easily accessible.
2. Components that function together should be grouped together.
3. Labelling should be clear and informative.
4. The need for specialised tools should be avoided.
5. Fine adjustments should be able to be made in the workshop and not in the field.
6. The design should assist maintainers to identify the location of faults."
   (p. 122)

These design principles accord closely with many of the problems reported by maintenance technicians in response to the *Design & Maintenance* questions in HFIT, demonstrating their role in maintenance failures.

5.4.4 Communication

The third most-frequently reported code in the interviews was *Communication.* In many of the interviews it was apparent that participants in the work process (e.g. maintenance technicians, engineers, suppliers, and planners) had failed to communicate needed information to other personnel. Not surprisingly, *Information* (#6) was also frequently reported as a contributor to these failures. The HFIT factor *Communication* consists of a number of items (Table 10) relating to lack of communication in the workplace, for example, communication that was relevant to the maintenance task that did not occur to the extent necessary to complete the task successfully. The second and third most common sub-factors were specific to the locus of this lack of communication, i.e.:

- between the target company and another organisation involved in the maintenance activity, such as a contractor, supplier, or agent
- between on-shore and offshore personnel, typically between maintenance technicians, and either engineers or planners.

The communication failures ranged from the most basic (e.g. from the supply of the wrong parts), through to the highest level of required information, (e.g., failure to advise about changing work procedures and major engineering changes). "Procedures and rules change all the time, but no-one feeds it back to us," said one fitter at his interview. Maintenance workers in other industries experience the same poor communication and lack of information, as Holmgren (2005) observed among railway maintenance workers. He found that deficient communication not only contributed directly to collisions and derailments, but also resulted in an under-utilisation of maintenance workers' skills.

The sub-factor *Lack of communication* represented a general failure to communicate, such as when changes to equipment, stock levels, procedures, or work plans had been made and the relevant personnel had not been advised. This has been explicitly described by interviewees in their own words as a “breakdown of communication.” *Lack of communication* also concerns systemic failures in communication, either because too many disparate parties are involved, or because ‘political issues’ have created impediments to communication. According to Sagan (1994), “organisational blind spots can hide failure modes” (p.234), particularly when subjects are not discussed because they reflect badly on an organisation’s self-image.

These organisation-wide problems with communication were clearly recognised by maintenance technicians. They indicated that there was often a general lack of communication with maintenance personnel, particularly mentioning engineers. As one mechanical fitter said, “Communication between the shop floor and the engineers is zip.” Another person commented that, “The system did not promote communication between parts inspectors and the [off-shore] end-user.” Interestingly, this mirrors the findings of studies in the medical industry (Alvarez & Coiera, 2006) which found that, despite occurring infrequently (i.e., 2% of recorded communications), communication between doctors and nurses was still responsible for 37% of the errors. As with nurses and doctors, status differences between maintenance technicians and engineers may similarly be one impediment to adequate communication.

Weak communication links between on-shore and off-shore parties were often mentioned in the interviews; for example, the difficulties with communicating the nature of problems to engineers on-shore. Similarly, personnel charged with effecting solutions had failed to inform others of critical aspects of the situation. This included not communicating observations that would have changed the assessment of the corrective maintenance work required, and vendors dispatching equipment without advising of important changes made to the equipment. “There was bad communication all around,” was the assessment of an example given by an interviewee. This has been described in examples from the medical industry (Horwitz et al., 2009) in which messages relating to hand-overs were not communicated properly, particularly when different disciplines were involved. In a similar way, flaws in communicating critical information may occur when ‘handing over’ projects from on-shore personnel to off-shore personnel.

There was also a reluctance to take the time to record or pass on useful information. One maintenance coordinator remarked, “A lot of guys don’t like sitting down and writing a 2 or 3 page procedure…the only good practice not being followed is passing on information.” This was particularly true in relation to any required up-dating of the on-line Information Management (IM) systems where work orders, procedures, and maintenance history are stored. There were many perceived difficulties with entering information into the databases in the IM systems. These included the difficulty of accessing the personnel who authorise the up-dating of information, and the length of the approval process. As with the medical industry, issues of status and authority appear to hinder efficient communication processes (Roberts & Tadmor, 2002). A maintenance coordinator said that gathering information and feeding it back into the system was “one of the biggest things I see as a problem.” This was similar to the situation for the nurses in a study (Tucker, Edmondson, & Spear, 2002) of the difficulties they face in finding time to correct deficient communication. As a result, information within IM systems remained inaccurate, impeding a critical organisational learning process.

In a number of incidents, computer-meditated communication, such as the SAP database used to create and transmit work orders, was considered the source of ineffective communication. Critical details required from notifications in the SAP database were reported as being missed due to information being inserted in the wrong place or being badly located (e.g. text at the bottom of the screen). Information communicated via the SAP database also did not allow for necessary clarification and discussion, as the electronic format does not tend to encourage a two-way exchange between people. Research on the quality of group decision-making using computer meditated-communication (Baltes, Dickson, Sherman, Bauer, & LaGanke, 2002) has shown that across numerous studies, significant differences have been found in the effectiveness of computer-meditated communication compared to face-to-face communication. Baltes et al identified a negative effect of computer-meditated communication on decision-making effectiveness in 15 studies, compared to nine showing a positive effect. Furthermore, in 13 studies the effect of computer-meditated communication on *Time to Decide* was negative, and no studies showed a reduction in the time needed to produce a decision.

From descriptions of the communication processes involved, it did not appear that technology was the limiting factor. Communication between on-shore and off-shore personnel is supported by a wide range of synchronous communication technologies, such as e-mail. Video-conferencing, which is known to improve the outcomes from decision-making of virtual teams (Baker, 2002), is available in the Perth office and the Process Plant. Rather, the workplace culture appeared to work against requests for either clarification or further information. An off-shore maintenance technician said, in relation to spares that had not been sent by the shutdown crew arriving from on-shore, "We thought shutdown was dealing with it and shutdown says, 'It's not really our job because you guys know the isolations.'" In several of the failures discussed it was clear that even basic information from easily accessible sources was not obtained at times. The inevitable result, as described above, was the need to rely on assumptions, ultimately leading to poorly-informed decisions and flawed solutions to maintenance problems. This is significantly different to the description of the use of *meta-scripts* in effective communication among military units (Zohar & Luria, 2003a). In Zohar and Luria's study, shared mental models contributed to the development of brief and meaningful communication, known as meta-scripts, which were readily understood by all participants. Processes aiding the development of better shared mental models between maintainers and on-shore planners, engineers and vendors would greatly reduce the mis-communication that appeared to occur between personnel having different conceptualisations of the tasks and requirements in off-shore maintenance.

The relationship of communication to the other human factors explored was instructive. *Communication* often occurred with *Assumption* in many of the failures. The frequent recurrence of *Decision-making* as a factor, with low reporting of *Competence* and *Supervision*, indicated that insufficient knowledge, training, or direction was not generally blamed by maintenance technicians for the failures. Instead, it appeared that deficient communication was frequently part of the mechanism through which assumptions were allowed to compromise the entire maintenance problem-solving process.

Finally, the results of Study 2 agree with Muchinsky's (2003) comments referring to a Systems Theory approach to organisations:

> With all these parts making up the system it is necessary to have a means to provide coordination and linkage among them. Such functions are accomplished through *communication and decision-making* [italics added]; they permit the various parts of the system to 'talk to each other'. (p. 250)

5.4.5 Other considerations evident in the failure data

Omission was the fourth most frequently reported contributor to failure. As well as instances in which critical steps were omitted from a work procedure, this category also included failures due to:

- Neglecting to up-date procedures. This impacted on *Procedures* and *Information*.
- Neglecting to check the suitability of a part or procedure about to be used. This is closely related to cases involving assumptions concerning the suitability of spare parts.
- Final checks not being done on equipment after maintenance, which was also an issue of *Teamwork* and *Supervision*.

Omissions are a category of human error frequently examined in the study of NPP maintenance failures mentioned previously (Pyy, 2001). Along with errors of commission they form one basis for analysing the cognitive causes of human error. In terms of the human errors reported in the Study 2 interviews, the total for errors of commission (reported in the HFIT model as *Timing, Selection, Execution,* and *Work Quality*) was cumulatively higher (74% of cases) than for *Omissions* (58% of cases). This represents a ratio of errors of commission to omission of 1.3:1, whereas in Pyy's incident report data, the ratio is ~3:1. In the interviews, opinions regarding the non-performance of tasks, such as checking for errors and obtaining additional information were often reported. This resulted in almost equal numbers of errors of commission and omission, compared to the written reports in Pyy's study, in which errors of commission were reported preferentially.

Difficulties encountered with *Procedures* (#6) contributed to a frequent lack of information. When required task procedures were either not available or provided incomplete information, finding information became a necessary step in completing the job. However, developing shared mental models depends on having information in common (Mathieu, Goodwin, Heffner, Salas, Cannon-Bowers, 2000), which is one of the functions of a procedure. In several cases it was found that barriers to team members' communication, coupled with poor procedures, increased the potential for faulty problem-solving, and ultimately increased the potential for failure. The comments from several maintenance technicians concerning failure to pass on information indicated an awareness of effective team processes. However, the discrepancy between understanding good team processes and the difficulties of implementing these processes was a situation also observed among hospital teams (Flin, Fletcher, McGeorge, Sutherland, & Patey, 2003).

Many of the comments indicated that *Information* (#7) tended to flow in a single direction only. Information was provided to maintenance technicians via procedures and work orders, but often did not allow for the feedback needed to clarify ambiguities, obtain further information (e.g. to correct procedures), or resolve conflicting information (e.g. confusion concerning part or unit numbers). Effective feedback loops, such as those between maintenance technicians, engineers, vendors, and the company's Information Management systems were required to reduce the risks of mis-information. From the interview comments, the failure to request clarification or provide feedback did not seem to represent a lack of interest on the part of maintenance technicians, or the absence of needed technologies within the company. It appeared to relate to the difficulty experienced by maintenance technicians in using these systems, both in accessing information, and in the restrictions on entering information into them. The origin of this appeared to be threefold:

1) Procedures were reported as rarely available for maintenance tasks, in contrast to the activities of Operations personnel, which are heavily proceduralised. The procedures that do exist were reported as often being out-dated (particularly for older installations), not reflecting changes to plant, or not providing enough critical information for less-experienced maintenance technicians.

2) Engineers, rather than on-site maintenance technicians, are considered knowledgeable about maintenance procedures. The current process requiring engineering authorisation for amending procedures, while justifiable in terms of authenticating information, has created a situation in which the knowledge held by maintenance technicians is not captured in the Information Management systems. One person reported that maintenance technicians were not allowed to print procedures, in case they annotate them and work from annotated copies. This runs contrary to Hughes' comment (1951) that the 'colleague-group' should have the ultimate say over what constitutes good practice, because they "alone fully understand the technical contingencies" (p. 323).

3) There is a multiplicity of IM systems, including Virtual Bookshelf, MCP, SAP, First Priority, ALIS, the engineering drawing database, and electronic versions of vendor manuals. In regard to one failure at the Process Plant resulting from an incorrect Bill of Materials (i.e. spare parts list), the person involved reported that the data in SAP was not reliable, and therefore it was necessary to check several sources of information before starting a maintenance job. Quoting one maintenance technician from the Process Plant concerning access to needed information:

> "I would never trust the data in SAP…Information is not easily at hand, ever! If we get a work order to go out to calibrate something, we might have a third of the information we need to really, properly carry out the job. You go to a different system to look for the data sheets, another system to find out what happens if we trip a transmitter."

Another maintenance technician reported spending six hours trying to source information for a job. In a time-constrained environment, most maintenance technicians would not have this much spare time, let alone patience.

Importantly, there were a number of factors reported less-frequently in the interviews than was expected based on their prominence in the organisational psychology and management literature. Of factors expected to play a greater role in failures, *Competence & Training* was ranked 8th, *Supervision* was 17th, *Work Quality* was 19th, Teamwork was 20th, and *Violation* was 22nd out of the 27 possible HFIT factors. The literature on maintenance error in other industries (Reason & Hobbs, 2003) often attributed the cause of failure to various elements of human error, such as loss of situation awareness and incorrect selection. These were also not reported frequently as factors in the interviews. Given the willingness of interviewees to discuss even sensitive issues, and the high number of factors that were reported in each failure (*M*= 9.5 codes), it seems likely that the infrequently reported factors do not contribute significantly to the probability of failure. For example, the competence of maintenance personnel rarely arose in the failures reported, as evidenced by the low number of incidents identifying *Work Quality* (#19) as a factor. Maintenance technicians were closely questioned regarding work quality issues, if there was an indication that this might have been a contributing factor. However, when it had been a factor, there was generally no reluctance to discuss the circumstances.

One possibility is that a substantially different set of human factors are responsible for failures within the company's operations compared to organisations studied in the past. As mentioned, maintenance in petroleum industry operations tend to be less proceduralised than in equivalent aviation and NPP operations, resulting in fewer opportunities for procedural violations. However, a more likely scenario is one in which, as Einstein (1926) contended, the model used determines what is seen. As the human factors literature demonstrated, and First Priority data confirmed, most failure models focus on the role of human errors and rule violations, to the exclusion of group-level and organisational-level factors. Contrasting this, the interview data demonstrated that other more fundamental organisational processes consistently influence organisational performance.

Finally, in terms of facility type, the Process Plant demonstrated the effects of a less-experienced workforce, as noted by several interviewees. *Competence & Training* and *Supervision* were reported significantly more frequently there than off-shore. Conversely, the platforms and FPSOs demonstrated the constraints of off-shore facilities, in which human, technical and informational resources are more limited than on-shore. As a result, work planning and the availability of documentation were more frequent contributors to failures off-shore than in the Process Plant. Otherwise, there were few distinct differences between facilities. The conclusion to be drawn from this is that, aside from the exceptions mentioned, many of the factors revealed by HFIT are endemic to the organisation, and occur with all types of incidents and in all work areas.

5.4.6 Comparison of interview data with First Priority data

Studies 1 and 2 relied on the analysis of past adverse events to develop an understanding of the role of human factors in failures. Analysis of incident reports in First Priority was exploratory due to concerns about the quality of the data collected in the company's incident reports. As a preliminary study it has served two worthwhile purposes, i.e., the First Priority data 1) provided an indication of the representativeness of the incident to be explored in the interviews, and 2) demonstrated the areas in which company failure investigations could be improved in order to more accurately identify the human factors contributing to failures.

Examination of the demographics of staff (Table 5) indicated that the interviews conducted were approximately representative of the workforce in the company, though there were anomalies in the sample population due to the constraints on the availability of personnel for interviews. The distributions for Work Category and Production Type formed a representative sample of the workforce, with a few exceptions. The Major Maintenance team was over-represented compared to off-shore Core Crew, due to easier access to personnel for interviews. Similarly, supervisors and coordinator/planners were over-represented due to greater ease of contacting them for interviews. Comparison of the incidents in Study 2 with those in Study 1 indicated that severe failures were over-represented, and minor incidents were under-represented, possibly due to the tendency for people to focus on incidents with more serious consequences (Glendon, Clarke, & McKenna, 2006). Although a strictly representative sample of plant failures was not obtained, a bias among interviewees towards more severe incidents served to provide an emphasis on the factors that lead to failures with greater consequences.

Regarding quality of data, the information reported in the incident database was rich in event descriptions, but poor in contextual and motivational analysis compared to the interview data. A mean of 2.3 codes (SD=1.48) was reported for the incidents entered in the First Priority database, whereas the interviews had a mean of 9.5 codes per incident (SD=2.25). This demonstrated that a much broader understanding of the human factors in a failure is obtainable by appropriate use of a suitable investigation tool.

The data obtained from the interviews was also different to that obtained from company incident reports. The most-frequently reported factor in the First Priority data was that of procedural violations, with the quality of guidelines and procedures being a secondary factor. This tended to agree with the finding of the National Transport Safety Board in the US (Collier, 2004) that 76.5% of adverse events in aviation related to maintenance involved 'failure to follow procedures', as well as Boeing's estimate (Rankin, 2007) that ~40% of maintenance events are caused by violations. However, the occurrence of violations was viewed differently in the interviews. The occurrence of violations was a contributing factor in several of the interviews, particularly at the Process Plant, in which both insufficient supervision and the difficulty of accessing information on acceptable work practices were recognised as contributing to poor adherence to procedures. Although procedures were not followed in the incidents examined, the secondary nature of procedural violations was apparent in the interviews. Despite being closely questioned about whether or not procedures had been violated, maintenance technicians were of the opinion that few tasks were adequately proceduralised, and they often contended that greater attention to existing procedures would not have prevented the failure under discussion.

The next most prominent factor, *Design & Maintenance*, was the second most frequent factor in both First Priority and in the interviews. This reinforces the view that original designs greatly influence the ability to maintain plant. It may also indicate that the technical component of failure is more readily recognised in investigations than most other human factors. A focus on technical factors was discussed by Bea (1998) who considered that design engineers do not tend to concern themselves with the human support systems required for engineered systems, and similarly tend to recognise mainly the technical aspects of failures.

Finally, *Detection* and *Decision-making* were the third and fourth most frequent factors respectively in the First Priority data, while 11th and 5th, respectively in the interview data. The reporting of various forms of human error might be expected where third parties, such as supervisors, are responsible for attributing the causes of failure, as often occurred with First Priority incident reporting. As Dekker (2006) commented in his description of Hindsight Bias, 'failure to detect' (i.e. loss of situation awareness) and 'poor decision-making' are forms of human error that are attributed in hindsight when determining 'what people should have noticed' and 'what people should have done'. As expected with Hindsight Bias, the incident reports tended to over-report human faults, i.e. errors and violations, while neglecting to analyse more deeply performance shaping factors in the organisation. This in itself was an important finding of Studies 1 and 2.

The differences between the factors reported in First Priority and the detailed descriptions of incidents obtained in interviews highlighted the need to investigate beyond 'violations and errors.' The interviews revealed the role of communication and assumptions, often the result of difficult access to information, as among the mechanisms frequently provoking erroneous decisions and actions. In addition, the poor quality of and lack of access to procedures was considered a contributing factor more than twice as often as violations of procedures, indicating the organisation's role in the occurrence of violations. In their analysis of the typology of violations, Reason, Parker and Lawton (1998) considered that certain types of violations were caused by the actions (and inaction) of organisations. Study 2 demonstrated that by using an appropriate method, these actions and inactions of organisations that provoke errors and violations might be identified.

5.4.7 Evaluation of methodology

In conducting the interviews in Study 2, the intention was to identify the predominant human factors contributing to failures in the target organisation in order to investigate underlying organisational weaknesses. However, classifying human actions, and understanding how they relate to existing organisational systems are two distinct processes. In Dekker's (2003b) treatise on the subject, he enumerated the pitfalls of taking one for the other. "Relabelling error rather than explaining it…Mistaking classification for understanding"(pp. 95-6), and 'disembodying data' by classifying it into error categories, are all potentially valid criticisms of the attempt in Study 2 to reduce the complexity of 38 past events to 27 'causal' codes.

In particular, Dekker (2007) levelled his harshest criticism at the process of counting errors in many of the schemes for failure investigation. He decried this form of human behaviour analysis as both obscuring the difference between causes and effects, as well as supporting the conceptual status quo. In counting numbers of errors, they are removed from their context and in so doing, decrease any understanding that could otherwise have been gained. Dekker (2003b) instead advocated a move to understand "how universal patterns of breakdown occur repeatedly across operational particulars" (p. 104).

Bearing in mind Dekker's caveats, the intention of Study 2 was not to tally the number of mistakes made by maintenance technicians or ascribe causal relationships between their actions and the breakdowns in the incidents analysed. For this reason, all contributors to a failure were recorded with their supporting discourse, not only the root cause or primary causes, in order to retain the richness of the less prominent contributors to each incident. Although the methodology of Studies 2 and 3 did rely on quantitative analysis of the most frequent factors, examination of the qualitative discourse from the interviews was one step taken to avoid what Dekker referred to as 'digitising the data.' The aim of Study 2 was to identify patterns of breakdown in the maintenance process in order to provide the context required to investigate the relationship between human factors and reliability in Study 3. A pattern of incorrect assumptions, flawed communication, and problems encountered with plant design was identified as recurring in failed maintenance activities in the target organisation.

HFIT was found to be a suitable tool for obtaining this information on the recurring contributors to failures from maintenance personnel. It allowed for examination of a broad cross-section of factors that were recognised in the literature as being responsible for failures and poor performance. With the reformatting and modifications described in Section 4.2.2.2, HFIT provided a basis for obtaining quantitative data, as well as supporting comments concerning the incidents that could be subjected to qualitative content analysis. A content analysis was not undertaken in Study 2, as the quantitative data provided sufficient information to fulfil the objectives of this study.

From the interview results, direct discussions with maintenance personnel was found to be a suitable means for obtaining information, regarding the role of human factors, as maintenance personnel:

- are directly responsible for outcomes and, compared to engineering and maintenance planning staff, their work places them in close proximity to the effects of failure
- have a better understanding of the historical and current factors impacting on the reliability of equipment, in contrast to operations staff who often do not have the opportunity to observe the causes of, or solutions to, equipment faults
- often acquire an analytical perspective on archetypical and repeating systemic failures, and, being embedded in the production systems, often understand the systemic nature of failures better than managers do.

Obtaining failure data by the interview methodology also had several potential drawbacks, namely:

- Inaccuracies often occur in the recall of events. A failure investigation conducted at the time of the event, with an appropriate level of human factors expertise, would provide more accurate information.
- The interviewee's interpretation of events, as well as the interviewer's interpretation of the responses to questions and identification of the human factors involved, could bias the results obtained.
- Interviews were time-consuming relative to the quantity of data obtained. In theory, considerably more data could be obtained more quickly from a database designed for logging investigations of failures recorded at the time of the event. Collection of data on minor incidents and near misses has been shown to improve the ability to estimate the risks of major failures (Jones, Kirchsteiger, & Bjerke, 1999). However, investigators with human factors expertise would be required to provide the quality of analysis needed. The First Priority database, described above, was found to lack the required level

of human factors analysis, and instead, reports were overly focussed on human errors and violations in many of the incidents, which Rasmussen (1990) considered to be 'fragments of behaviour'.

- The interview study sample size was small, reducing the statistical power of the study. Accessing information on failures in company records provided a larger sample population, but at the expense of quality in the data.
- Obtaining cross-sectional data required a broad cohort of interviewees. Accessing maintenance personnel working off-shore was found to be difficult and therefore this group tended to be under-represented in the study population.

Attributional differences in the rater's interpretation of the interviewee's responses also complicate interpretations. Even with a clear 'Yes/No' response to the interviewer's prompting question, the interviewer as human factors expert may need to re-assign the response to a more theoretically appropriate category, based on an understanding of the issues under discussion. This too will introduce biases in categorising responses. Some areas of questioning require added sensitivity to both obtain an objective response and to avoid antagonising the interviewee (Patton, 2002). For example, questions concerning violations of procedures or inadequate supervision might imply blame of the interviewee or someone close to the interviewee. Modifying the questions during the interview and probing for additional detail was sometimes needed to explore sensitive aspects of several of the incidents.

Finally, as a consequence of the above, considerable care in interviewing and analysing responses was required to avoid the pitfalls of either under- or over-interpreting the interviewee's responses. It was clear from the evaluation of HFIT, and Wallace and Ross' (2006) discussion of the main causes of variability in inter-rater reliability, that failure investigators need to have an understanding of the human factors issues, as well as a clear understanding of contextual issues in the failure domain. Further research is required to refine HFIT for a specific domain, which could include removing overlaps between codes, clarifying the terminology used, and restructuring the sequence of questions. These refinements will then need to be subjected to further testing for construct validity and inter-rater reliability to ensure that the questions and codes adequately describe the human factors existing in the particular context.

5.5 Summary and Conclusions

Study 2 demonstrated that interviews with maintenance personnel provided a better means of identifying contributing factors in maintenance failures than the company incident reports examined in Study 1. Using the taxonomy in HFIT, structured interviews (N=38) were conducted to determine the human factors which recur most frequently in maintenance failures in the petroleum industry. Interviews conducted with maintenance personnel identified *Assumption*, *Design & Maintenance,* and *Communication* as the three most-frequent contributors to failures. Assumptions were most often made concerning the correctness of procedures being used, and that the correct parts and systems were being repaired. Designs and inadequate maintenance were most frequently recognised as a problem when original designs made maintenance difficult or created confusion which ultimately led to the wrong maintenance activities being conducted. Lack of communication most often caused failures when various parts of the organisation failed to provide required information, or maintenance personnel failed to contact other participants in maintenance activities to clarify information.

These results agreed with many previous studies of the impact of human factors on performance. Consistent communication and a focus on methodical problem-solving represent fundamental organisational processes that have been identified in the HRO literature (see Section 2.11.3) as requirements for high reliability. In addition, CRM in the petroleum industry (see Section 2.9.1) focuses on communication, situation awareness, and decision-making as important to reliable and safe operations. The complexity of petroleum production systems requires situation awareness and attention to methodicalness, as the high rate of assumptions demonstrated. Similarly, plant design and maintainability, the second most-frequent contributor to failures, have been identified in the engineering and human factors literature (see Section 2.6.1) as important determinants of the ease of maintaining plant, and in turn, the performance of maintenance groups. These three factors were often found to occur in association with related contributing factors. Thus, a mean of 9.5 codes were identified for the failures examined. Faulty decision-making, lack of task-related information, and poor quality and limited availability of procedures, all were frequent secondary contributors to the ‘pattern of breakdown’ that frequently involved flawed assumptions, plant designs, and communication.

The less frequent contributors to failure also provided valuable information about the performance of maintenance groups. *Supervision* (#17) was rarely a factor, reflecting the high degree of autonomy and wide geographic distribution of maintenance personnel that distinguishes the petroleum industry from the aviation and nuclear power industries. Similarly, *Teamwork* (#20) as a factor was rare, as the interviews revealed a high degree of cohesiveness between team members, and between teams and their supervisors. Despite the attention given to rule violations in the human factors literature, *Violation* (#22) rarely contributed to failures. Maintainers queried about possible procedure violations reported that relatively few maintenance tasks, compared to control room operations, were specified in procedures. These results demonstrated that a number of human factors that are prominent in many research studies, particularly in the aviation and NPP domains, appear not to be as relevant in the context of petroleum production.

5.5.1 Application of the results to Study 3

Study 2 provided an indication of the influence of specific human factors on past failures of reliability in petroleum operations. This study indicated which human factors recur in individual failures. Study 3 will be conducted to characterise the relationship between human factors and the outcomes of maintenance activities, in terms of the day-to-day reliability of petroleum operations. This will involve a comparison of the three most-frequently occurring factors identified in Study 2 against group differences in reliability level. To accomplish this, a measure for ranking the reliability level of different company work areas will be required (Chapter 6). In addition, measures will be needed for assessing work area differences in these three recurring human factors (Chapter 7).

6.0 Identifying a Reliability Measure of Maintenance Work Areas

6.1 Introduction

6.1.1 Linking failures to reliability

In order to link the results of the previous study to Study 3, a conceptual connection between failures and reliability is required. According to Dhillon's (2002) definition, "reliability is the probability that an item will perform its stated mission satisfactorily for the given time period when used under the specified conditions" (p.183). When the item no longer does this, it is said to have *failed*. Thus *reliability* and *failure* might be considered opposite poles of the same dimension. In addition, reliability is often compromised by minor adverse events. Research into accidents has demonstrated a model of organisational safety, in which minor events are closely linked to serious accidents (Wallace, Ross, Davies, Wright, & White, 2002). Wallace et al believed that many of the serious failures over the past 20 years had been "preceded by relevant near misses" (p. 1). Other researchers have supported the concept of near-miss/minor events as an indicator or predictor of the risk of major accidents. Jones, Kirchsteiger, and Bjerke (1999) cited the commonly-accepted *safety triangle*, in which near misses provide a pool of events from which minor injuries and in turn major accidents are drawn. They quoted ratios of near misses to minor injuries to major accidents (i.e., 600:10:1) derived from accident data. In a similar way, the minor events that impact on reliability statistics provide the pool of events from which failures may eventuate.

Based on a relationship between minor events and failures, Study 3 will test if the same factors that contributed to the range of failures discussed in the interviews in Study 2 also influence the occurrence of minor events that determine the day-to-day reliability of plant and equipment. In Study 2, retrospective investigations of failures conducted with maintenance personnel demonstrated that the most-frequent contributors to failure in a petroleum operation were *Assumptions, Design & Maintenance,* and *Communication*. These dimensions will then to be used in Study 3 as the basis for quantifying the influence of human factors on the reliability of workplaces.

6.1.2 Review of reliability measures

In reviewing the literature on reliability, it was apparent that different measures were in use in industrial organisations. Lofsten (2000) surveyed eight major Swedish manufacturers and energy producers, and found a wide range of reliability and efficiency measures had been adopted to quantify maintenance performance. Most concepts of reliability focused on production outcomes, but others were indications of actual maintenance performance. Even the International Standards Organization (2006b) commented that "No single KPI [Key Performance Indicator] provides the complete picture and it is, therefore, necessary to define a basket of KPIs that together indicate progress and trends in reliable operation of plant and equipment" (p.160). Furthermore, as Todinov (2004) commented, reliability measures will depend on the use the measures will be put to, such as "minimising the financial risks associated with loss of production" (p.273) and that different reliability measures will be needed in different industries, as they are expected to experience different failure modes. Despite the perception of engineering measures as universal, an engineering concept such as *reliability* may still manifest itself in different emergent properties of a technological workplace. Therefore, a quantitative measure specific to the research context is required. Consequently, selection of a suitable reliability measure is an important component in the ranking of work areas for Study 3, and requires as much consideration as selecting the measures for assessing group differences in human factors.

6.2 Measures

6.2.1 Engineering theories of reliability

Considerable research has been devoted in the engineering literature to theoretical considerations of equipment reliability. In studies such as Zequeira and Berenguer's (2006) these considerations have consisted mainly of academic analyses of the failure rates of hypothetical components, functioning as a part of a system model, and operating under idealised conditions. In other research (Saleh & Marais, 2006), the objective has been more empirical in nature; that is, consideration of operational reliability has been based on either critical safety criteria or critical production criteria.

Sharma and Kumar (2008) offered a theoretical definition of reliability as "a measure of the *probability of failure-free operation* during a given interval" (p.893), which Sharma and Kumar represented mathematically as the probability (R) at time (t) for a failure rate (λ):

$$R(t) = e^{-\lambda t}$$

As the failure rate (λ) approaches 0, the probability of failure-free operation approaches 1. Integrating this quantity over time provides a closely-related reliability function, the Mean Time To Failure (MTTF) (Dhillon, 2002 p.187):

$$\text{MTTF} = \int_0^\infty R(t)dt$$

Analysis of Mean Time to Failure in its simplest form can be an analysis of a single component operating independently, and subject to a constant failure rate. This will then become a more complex situation if the component:

- has a non-constant or unknown failure rate (Todinov, 2004)
- is part of a serial network, in which the loss of any component compromises an entire system (Dhillon, 2002), or
- is part of a parallel network, in which redundancy reduces the probability that a single failure will compromise the whole system (Dhillon, 2002).

As the system becomes more involved, it becomes more difficult to represent systems mathematically, particularly when actual failure rates are not known. Bayesian approaches (Antelman, 1997) have been developed for these more complicated situations, in which the expected failure rates are estimated from accumulated empirical data, rather than from theoretical principles.

Ultimately, rather than pursue mathematical representations of reliability, many industrial organisations have been concerned with empirical measures of operational reliability, which represent the actual performance of units of production, or the probabilities that a production loss will occur. These measures then provide a basis for identifying problem areas, assessing the efficacy of interventions, benchmarking against similar operations, and translating operational measures into economic measures (Saleh & Marais, 2006).

6.2.2 Measures of reliability in industry

In order to accommodate a broad variety of industrial systems and potential failure modes, a range of empirical measures have been adopted to quantify plant and equipment performance. These are sometimes defined as the organisation's 'key performance indicators', which indicate the measures that the organisation believes best represent its performance, both in relation to its own past performance and to the performance of other similar operations. Given that the objective of production-critical operations, such as in the petroleum industry, is to maintain production output to a required level, an ability to monitor problems that may be developing in sub-systems and individual components is an important reliability function.

The following are measures for monitoring performance that are currently employed in production-critical industries, several of which are commonly-used reliability measures, and others that are more specialised in their application:

- Mean Time To Failure (MTTF), which was presented in the previous section as a mathematical function, is also evaluated from failure history. It is derived by averaging the occurrences of failure of a component or system over a period of time to determine the mean operating time without a failure. This can also be expressed, for components that are repaired, as Mean Time Between Failures (MTBF), which takes into account the Mean Time to Repair (MTTR) as follows:

$$MTBF = MTTF + MTTR$$ (Dhillon, 2002)

- Minimum Failure-Free Operating Period (MFFOP): the time interval during which a failure will not occur to a given probability. This is an important statistic for aircraft in flight and other time-based operations (Todinov, 2004).
- Availability: percentage of time equipment is available to carry out its function. All maintenance activities are included in the downtime. Availability can be considered as an operational measure or an intrinsic measure depending on whether it is calculated from actual uptime or actual repair times, respectively (International Standards Organization, 2006b). These can be expressed as:

$$\text{Operational Availability}(A_O) = \frac{\text{Mean Uptime}}{\text{Mean Uptime} + \text{Mean Downtime}}$$

or

$$\text{Intrinsic Availability}(A_I) = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR}}$$

- Unplanned Downtime (UDT): the total out-of-service time, from the time an item fails to the time it is restored to service (International Standards Organization, 2006b). The ratio of unplanned downtime to total downtime provides an indication of the effectiveness of maintenance, as ideally all downtime should be planned preventative maintenance, with little or no unplanned breakdown maintenance. As Aoudia, Belmokhar and Zwingelstein (2008) found in their study of the maintenance of a petroleum company, planned downtime was responsible for 2% of unproductive plant time, while unplanned downtime contributed 66% of unproductive time.
- Overall Equipment Effectiveness (OEE) is a measure of all the losses in productivity attributable to particular machines or systems, and provides a basis for comparing different production systems (Bamber, Castka, Sharp, & Motara, 2003). The expression for Overall Equipment Effectiveness is:

  OEE = Availability (%) x Performance rate (%) x Quality rate (%)

  Availability refers to Operational Availability as defined above, *Performance* is a measure of speed or capacity relative to ideal rates, and *Quality* is a measure of losses due to quality defects. While OEE is generally more applicable to manufacturing operations, Bamber et al. considered that OEE was “appropriate to all operations containing plant and machinery” (p. 223).

6.2.3 Reliability measures used by the target company

6.2.3.1 Key Performance Indicators

The target company for this research collects empirical data concerning a range of key performance indicators to monitor the performance and reliability of maintenance work across entire facilities. Among these are indicators of engineering integrity - the reliability of safety-critical components and systems, and maintenance integrity and effectiveness - the ability of maintenance teams to complete critical maintenance tasks effectively. Most of the indicators record the completion or non-completion of tasks that are considered critical to technical integrity, that is, safe operation. These tend not to reflect either the quality of work done or the long-term outcomes. As was demonstrated in the cases investigated in Study 2, faults may arise in the course of completing maintenance tasks, which then result in problems at a later stage. Pyy (2001) in his research on NPP shutdowns found that 49% of failures originated from completed shutdown activities. In a study by Svenson and Salo (2001), 40% of the errors made in nuclear reactor maintenance had not been detected within 10 weeks of the work being completed.

Availability is one of the company's maintenance integrity measures that does reflect long-term outcomes from maintenance. It is a facility-wide statistic recording equipment availability as a percentage of the production plan. As indicated in the literature (International Standards Organization, 2006b), *Availability* would generally be a useful basis for comparing maintenance workgroups, as the ability to utilise equipment when it is required for production indicates a successful maintenance program. However, examination of the *Availability* data for the Year 2009 indicated a large variance in monthly data. In addition, a proportion of the assessments indicated "100% availability," which were questionable and did not provide a basis for comparison between facilities.

Another item, named the *Fail-to Danger (FTD) Ratio* indicated the number of maintenance notifications that were considered to have involved a component failing and creating a hazardous condition. It is a measure of the ability to intercept hazardous failures before they occur, reflecting on the effectiveness of the maintenance strategy. While this is conceptually an important dimension, the numbers of these occurrences was low, for example, typically less than four per month per facility, with a large monthly deviation. Zohar (2002a) commented that low frequency events do not provide a statistically useful basis for distinguishing performance differences. He cautioned that obtaining accurate group-level data is often difficult due to small sample population sizes. His views apply equally well to measuring the effects of human factors on industrial reliability, as in the current research. His solution was to analyse the frequencies of minor injuries, rather than the more commonly used Lost-Time Injury (LTI) rate. An equivalent approach in reliability would be to monitor the frequency of *trips* or plant stoppages, rather than major breakdowns. This is the methodology that has been adopted for Study 3 of this research.

6.2.3.2 Data in the maintenance history database

A Systems Application and Products (SAP) database is used by many industrial companies, including the target company, to record ongoing financial, maintenance history, supply chain, and operational data. This includes detailed information pertaining to the request for, generation of, and completion of maintenance work orders. Work orders are daily events including routine maintenance tasks, and as such tend to include large amounts of data. The following maintenance effectiveness data is recorded by the target company in the maintenance area of their SAP database:

- Number of maintenance tasks flagged as breakdowns
- Mean Time Between Failures (MTBF) for individual components
- Mean Time to Repair (MTTR) for individual components
- Production-critical unplanned downtime.

All of these reflect, with varying degrees of accuracy, the effectiveness of various maintenance processes within a company work area. The accuracy of data however depends on a subjective assessment of the maintenance task by the maintenance technicians involved. The actual time devoted to a task is often not reported accurately and other characteristics of the job (e.g. flagging breakdowns and production-critical jobs) are also routinely not entered into the database upon completion of work orders. Hence, in Comerford's (2009a) opinion, confidence in the accuracy of this data is not high among the company's reliability engineers, and its usefulness for comparing work areas is limited.

Each of the key performance indicators collected by the company indicates a different aspect of maintenance planning, efficiency and effectiveness. A comparison was made between two of these performance indicators in SAP, namely the Mean Time to Repair and the Mean Time Between Failures as an average of all components across an entire facility (Figure 5). MTBF and MTTR are derived from the repair history of each piece of equipment, and are calculated from the number of times an item is out-of service for repairs in a set period of time. Data was extracted from SAP for 12 months during the period April 2008 to March 2009. As Figure 5 indicates, aside from the outlier Gas Platform 3 there is relatively little difference between facilities in Mean Time Between Failures. As these measures are calculated across all components regardless of the size or criticality of equipment, there is an insufficient basis for differentiating between facilities.

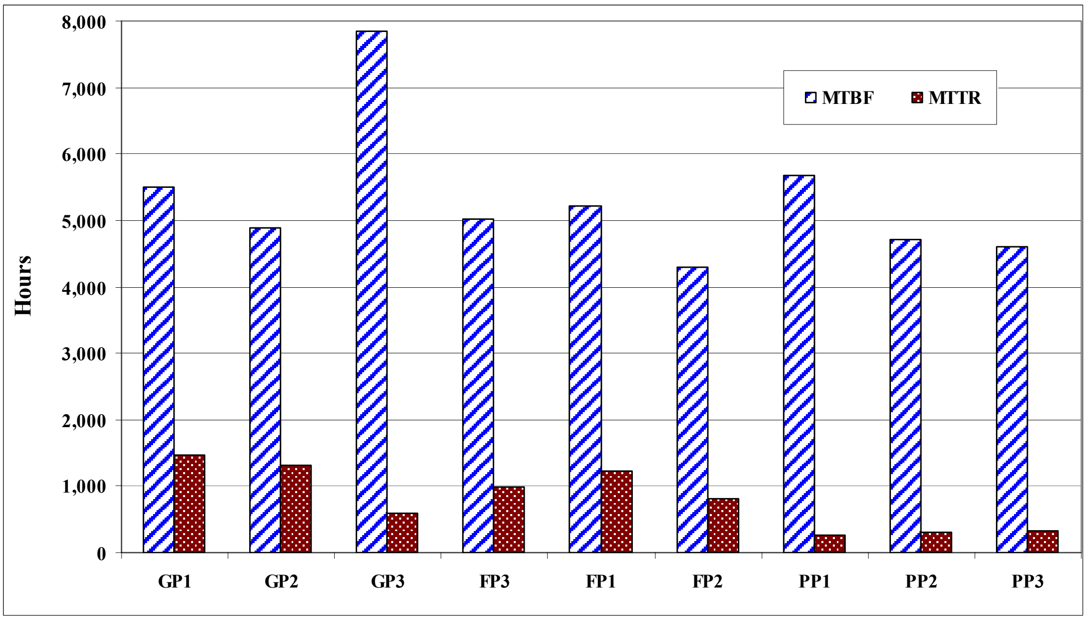

Figure 5. MTBF and MTTR recorded in a 12-month period (April 2008-March 2009) for each off-shore facility or operating area of the Process Plant.

Another measure that was examined for use in comparing work areas was the *Number of Flagged Breakdowns*. This involves absolute numbers of breakdowns, and so comparing facilities of different sizes requires the number of breakdowns to be normalised in order to account for the characteristics of the facilities, such as the size (number of operating components), complexity, age, and magnitude of the maintenance effort. Each of these factors will impact on the comparability of one facility with another in order to rank them according to reliability level. Thus, two facilities may be inherently equal in reliability. However, the facility with more items of equipment, more complex control systems, and fewer resources devoted to maintenance work will be expected to experience more breakdowns, more unplanned downtime, and will require more time to repair and maintain. For this reason, *Number of Flagged Breakdowns* was judged to be unsuitable for comparing reliability levels between work areas.

6.2.3.3 Production deferment data

Reliability Engineers at the company collect monthly data concerning a number of indicators of performance, particularly unwanted events and conditions that cause production losses, deferments, and downtime (Comerford, 2009b). Monthly data is analysed by a Facility Reliability Engineer as part of a process called the Operational Reliability Improvement Process (ORIP), which is reported in monthly reports. The data is reported both as a cumulative monthly trip rate as well as a Mean Time Between Deferments (MTBD) based on a 6-month running average.

A production deferment event was defined by the company (Comerford, 2009b) as,

> Any event that results in unplanned production loss or deferment which may include, but is not limited to:
>
> - Trips (ESD [Emergency Shutdown], PSD [Process Shutdown])
> - Unplanned Shut Down / Stop
> - Shutdown Overruns
> - Reduced output / Capacity
> - Delayed start-ups / restart (p.6)

For comparison, production trips were also defined in the relevant International Standards Organization standard (2006b) as, “the situation when machinery is shut down from normal operating condition to full stop” (p. 133), and can either be due to 1) exceeding control system limits, 2) a failure in an essential piece of equipment, or 3) an operator deciding to stop machinery due to concerns about the way that it is operating.

6.2.4 Selection of a reliability measure for Study 3

As the literature quoted in Section 6.2 indicated, various forms of Mean Time Between Failures are considered a standard measure of reliability. This type of measure is theoretically consistent with the definition of reliability provided in Section 2.3. Unlike absolute measures, such as the number of breakdowns per month or the total unplanned maintenance time per month, mean time between failures is a relative measure. For example, if two plants are operating to the same level of reliability, and the production rate of one is increased, the mean time between failures should remain the same for both. Similarly, if two compressors are being compared for reliability, despite one being older and one being more complex, equivalent reliability will mean that the mean time between breakdowns will be the same. The older compressors may have more parts needing replacement at each breakdown, and the more complex compressors may require more time to repair, and so will have lower available up-time, but this should not affect the reliability statistic. Therefore, a relative measure that allows for comparison of work areas within the company irrespective of size, complexity, or age of the facility, is likely to provide a better basis for assessing relative performance.

Although measures such as MTBF and MTTR for individual items of equipment were indicators of the effectiveness of maintenance tasks within the company, the data collected by the company did not provide stable and meaningful measures for comparison. The data collected concerning breakdown of individual machines, although indicative of maintenance effectiveness, was not assessed and recorded uniformly across the different work areas. In the case of MTBF of components, the long times between failures of some components tended to over-inflate the mean component lifetimes. Similarly, the MTTR data was thought to be over-inflated by components that were not critical to production and those that were redundant. In the case of non-critical equipment, repairs often take a long time from start to completion only because there is no urgency to completing the repair.

Plant production deferments are the performance failures of concern to the company as they represent a loss of production, which in turn equates to a financial cost to the company. Ultimately, the production deferment data is both directly relevant to the company's objectives, and also provides a holistic measure of how well a work area is able to regulate the processes that are required to achieve consistent performance of the plant. Unlike *Availability* (see Section 6.2.2), which is subject to interpretation as to whether equipment failed when it was required or failed when it was not required, deferments represents a production loss and lack of reliability. In addition, deferments occur sufficiently frequently to provide a useful statistical basis for analysis, unlike events which occur only rarely. For these reasons, production deferment data was selected as the measure for ranking the relative reliability levels of the work areas analysed in Study 3.

6.3 Analysis

6.3.1 Company work areas

As discussed in Section 4.1.4, within the company's operational facilities there are three different types of facilities, namely, off-shore gas platforms, off-shore FPSOs, and the distinct process areas within the Process Plant. Each of these types of facilities and the work areas within the Process Plant handles different products and utilises different processes. For example FPSOs mainly handle oil, and their operational processes involve separating oil from water and storing the oil in tanks on-board the vessel. Gas platforms extract, compress, and pump gas to the on-shore gas processing plant. The maintenance processes involved are therefore different and comparisons could only be made between work areas within a facility type. Within the company, three FPSOs and three gas platforms were identified. Additionally, three work areas within the Process Plant were identified. These nine distinct work areas constitute a 3 x 3 experimental design of facility types and work areas. The following review of production deferment data provides a comparison of the differences in reliability data collected for these nine work areas.

6.3.2 Analysis of production deferment data

Monitoring of production deferment data is now a routine monitoring task within the company, though complete collection of this data was only available from 2008 onwards. For the purposes of this research, production deferment statistics were extracted from data collected by Reliability Engineers as part of their reporting for the Reliability Improvement Process (Comerford, 2009b). Figure 6 displays data collected for a period of 12 months; higher values correspond to longer mean times between production deferments and therefore represent more reliable performance.

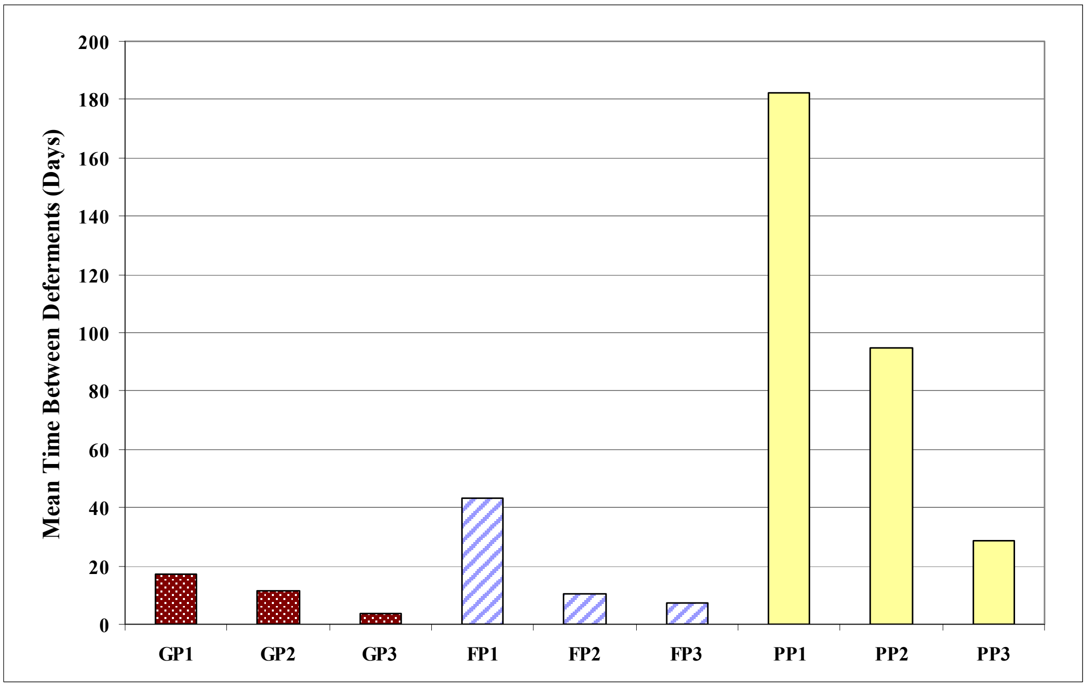

Figure 6. Mean time between production deferments for work areas.

In addition to assessing the mean time between deferments for a 12 month period, the rate of change in monthly mean value (Δ MTBD) was calculated in order to determine whether values were improving or becoming worse (Figure 7). Comparing Figures 6 and 7, it can be seen that among the off-shore facilities with better monthly mean times (i.e., Gas Platform 1 and FPSO 1), Δ MTBD was positive. For the work areas with lower monthly means (i.e. FPSO 3 and Gas Platform 2), Δ MTBD was negative. Thus the rate of change (Δ MTBD) often agreed with the absolute differences in MTBD between work areas. A different effect appears to be occurring in the Process Plant, which may be due to changes in local conditions. Gas Platform 3 is a new facility having started production the previous year (2007), and therefore improvements appeared to be occurring from a relatively low baseline.

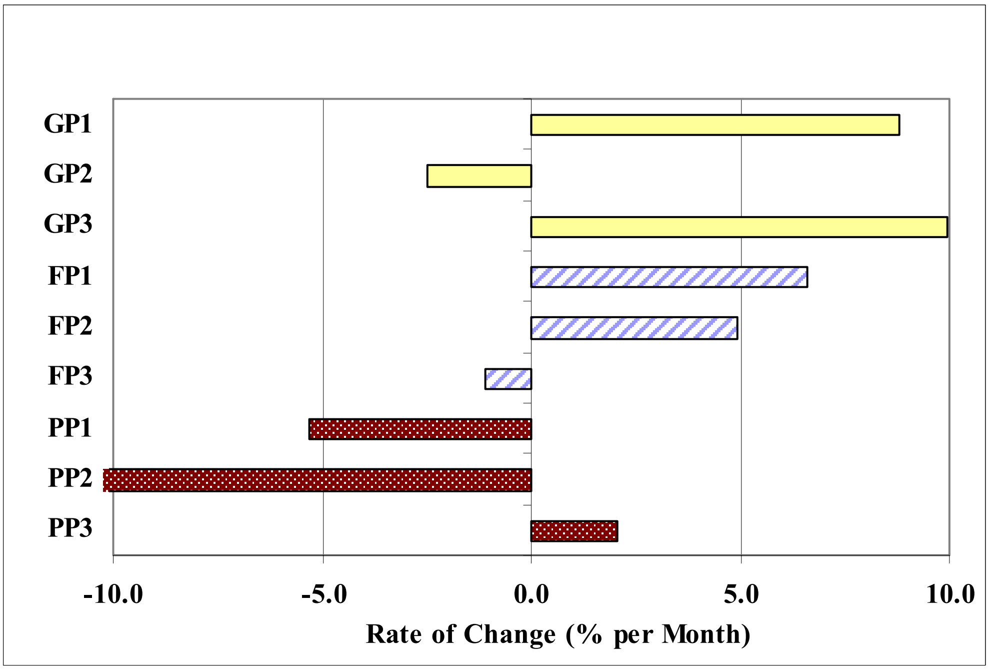

Figure 7. Rate of change of Mean Time Between Deferments (Δ MTBD).

Reliability rankings were assigned in Table 11 based on the deferment data presented in Figure 6.

Table 11. Reliability ranking of work areas based on mean time between deferments.

Reliability Ranking	FPSO	Gas Platform	Process Plant Area
Higher	FP1	GP1	PP1
Middle	FP2	GP2	PP2
Lower	FP3	GP3	PP3

6.4 Discussion

6.4.1 Relevance of the production deferment data

The production deferment data (MTBD) is a measure generated and accepted by the company as a measure of reliability with regard to the maintenance of critical equipment and achievement of company objectives. It has validity to the organisation because it captures the mean time between production failures, which agrees with Dhillon's (2002) definition of a reliability measure. Unlike the MTBF data for individual items of equipment extracted from the SAP maintenance history database, which include all components irrespective of degrees of importance, production deferments represent significant impacts on company performance (Comerford, 2009b). Furthermore, as a key performance indicator, the collection and analysis of this data was considered by Comerford (2009a) to be conducted more consistently across all of the facilities within the company, than for data that is analysed less routinely. The deferment data was the statistic that provided the most stable indication over time of the differences between facilities. In addition, it was based on sufficiently frequent events to allow for meaningful differentiation between work areas, and was therefore selected for assigning reliability rankings.

6.4.2 Ranking of company workplaces

The data in Figures 6 and 7 were based on the number of times production was deferred or stopped outside of planned stoppages in a 12-month period. They represent a range of unwanted events, which Aoudia, Belmokhtar, and Zwingelstein (2008) argued relate to the ability to effectively plan and conduct maintenance work on equipment. On the basis of mean monthly deferment data (Figure 6), a ranking of work areas within each facility type into lower, middle, and higher reliability was assigned (Table 11). Due to the differences in equipment, workplace structure, and task organisation, it was important to compare reliability among equivalent work areas so that facility type was not a confounding variable.

Further support for the rankings was obtained from calculations (Figure 7) of the rate of change of the monthly Mean Time Between Deferments (Δ MTBD). The rate of change indicated which facilities were experiencing improving reliability over the time of the research (i.e., longer mean times between deferments). It was found that the off-shore facilities that had the highest MTBD, namely FPSO 1 and Gas Platform 1, also often demonstrated the best improvement (i.e. higher rate of change in a positive direction). Having established a basis for ranking the relative reliability of the different work areas, it will now be possible to investigate the statistical relationship between human factors and reliability level in Study 3.

6.4.3 Implications for Study 3

In order to conduct Study 3, a measure of the maintenance reliability of each facility will be required. Lofsten (2000) found that such a measure could be elusive due to the different quantities measured as part of monitoring plant performance, as well as variations in the quality of the data collected. For this reason, rather than treat the MTBD data as scalar data, only ordinal rankings were assigned to the different facilities. For the purposes of Study 3, these rankings based on the MTBD data presented in this chapter are sufficient to analyse group differences in human factors.

6.4.4 Improvements to the methodology

Bamber, Castka, Sharp, and Motara, (2003) considered that improvement in an industrial organisation involves refinements to the monitoring of processes and outputs. Through theoretical and practical developments, this monitoring becomes more sensitive over time to actual differences, as well as more accurate with regard to obtaining consistent and reproducible measurements. Improving the collection of baseline reliability data should be an objective of further research into the impact of human factors on outcomes in petroleum operations.

The data was considered to have validity in capturing the construct of reliability, as the concept of reliability relies on the probability of operating without a failure. However, other confounding factors are also responsible for the occurrence of deferments, including natural variations in well production, faults caused by operators, or problems with other facilities impacting on local production. In terms of construct validity, monitoring breakdowns of specific production-critical equipment would provide a better indication of true maintenance-related reliability, as failure rates would be specific to distinct pieces of machinery rather that entire plant systems. However, this would require more systematic and uniform collection and analysis of data entered into the maintenance history database than currently occurs. This process could be started by monitoring specific classes of critical equipment (e.g. compressors, pumps, or process control units) and expanded to include most production-critical equipment.

Another advantage of monitoring individual items of equipment would be the increase in the quantity of data obtained for each work area. In his studies on the effects of leadership type on safety climate, Zohar (2002a) concluded that the size of population samples and low variance between groups is a difficulty with group-level research. He favoured basing assessments on measures which provided larger sample sizes, for example minor injury rates, rather than lost-time accidents that were relatively infrequent. As researchers have noted (Jones, Kirchsteiger, & Bjerke, 1999; Wallace, Ross, Davies, Wright, & White, 2002) minor event reporting provides a better statistical basis for characterising the safety of systems than small numbers of major accidents and events. Again, Mean Time Between Failure of a large number of production-critical items of equipment would provide better statistical information than fewer major events across an entire plant. Efforts to improve the methodical recording of MTBF data for items of equipment could provide a basis for improving the assignment of overall reliability levels to individual work areas. Further analysis would be needed to confirm the accuracy of MTBF data in defining quantitative differences between work areas.

6.5 Summary and Conclusions

Reliability is defined as the probability of failure, and can be calculated on the basis of the Mean Time Between Failures (MTBF). Although this class of data was collected by the company for individual items of equipment, it was not collected sufficiently methodically to be considered an accurate representation of differences between work areas. As a consequence, facility-wide Mean Time Between Production Deferments (MTBD) data based on trips and other plant downtime caused by a range of maintenance-related contributors, was considered the best available measure for ranking the reliability of facilities for Study 3. Although the use of MTBD was judged to be a sufficiently valid measure of ordinal ranking, further research will be required to confirm the validity of MTBD as a scalar measure of the maintenance-related reliability of an entire work area.

Based on the information supplied by Reliability Engineers as part of their Reliability Improvement Process reports, rankings were assigned to three gas platforms, three FPSOs, and three work areas in the Process Plant. The rankings assigned to off-shore facilities were generally supported by analysis of the rate of change of the MTBD. These rankings will be used in Study 3 as a basis for distinguishing the role of human factors between higher and lower reliability work areas.

7.0 Study 3 – Measuring the Influence of Human Factors on Reliability

7.1 Introduction

7.1.1 Review of Studies 1 and 2

Based on Rasmussen' s (1982) Model of Human Malfunction, HFIT has provided a suitable framework for analysing and understanding the human factors that contributed to failures within a petroleum processing operation. Study 1 (Chapter 4) has shown that the target organisation's incident reports most-frequently attributed maintenance failures to *Violations* of procedures and human error (i.e., errors of *Detection* and *Decision-making*). However, Study 2 (Chapter 5) demonstrated, through retrospective interviews with maintenance personnel that although violations and errors had occurred, the three most frequent contributors to maintenance failures were: 1) *Assumption, 2) Design & Maintenance*, and 3) *Communication*.

The aim of Study 3 is to measure whether the levels of the factors identified most-frequently in Study 2 differ between work areas with different day-to-day reliability of plant and equipment. The intention is not to generalise the findings concerning specific incidents, but rather use the results of Study 2 as an indicator of the most promising dimensions for a study of the role of human factors in reliability. In Chapter 6, it was argued that the Mean Time between Deferments (MTBD) is the most meaningful way to rank facilities with different reliability levels. Study 3 therefore uses this measure to determine the influence of the human factors of interest in lower, middle, and higher reliability work areas across each of the three facility types.

7.1.2 Selection of human factors measures for Study 3

7.1.2.1 Assumption

Assumption, the most-frequently reported HFIT code, was primarily related to a failure to investigate carefully the elements of the task at hand and obtain sufficient information (see Section 5.3). Thus there were essentially two dimensions of failures associated with the construct of *Assumption*, namely, decision-making and problem-solving. Faulty assumptions were found in most of the cases (57%) to be associated with cognitive processes leading to poor decisions in the reported failure. Often assumption-making was aggravated by a real or perceived shortage of time.

Insufficient information contributed to this process, as it led to applying assumed knowledge and past experience to decision-making. However, almost half (43%) of cases involving *Assumption* related to flaws in problem-solving, and were not found to involve an identifiable decision-making stage. In these cases, when *Decision-making* was not a factor, other aspects of problem-solving, such as failing to check the suitability of procedures or parts (*Omission*), were also reported. Failure to investigate the task methodically involved assumptions concerning the procedures and parts to be used, the condition of equipment to be repaired, or the potential response of the equipment to actions taken. In a number of cases, the problem solution was based on an assumption that the job was less complicated than it was, or that the planned action would improve the situation rather than make it worse.

Scales are required for Study 3 in order to measure the two constructs of *Problem-solving* and *Decision-making*. Only the *Problem-solving* scale in Morgeson and Humphrey's (2006) Work Design Questionnaire were found to contain items that would relate to problem-solving in industrial maintenance activities. As the authors explained, "Although there are thousands of studies investigating work and job design, existing measures are incomplete" (p. 1321), and consequently, they developed measures which could be used by practitioners investigating aspects of work design, including the requirements for problem-solving. The questions in the *Problem-solving* scale of the Work Design Questionnaire were previously included as the *Problem-solving demand* scale in Wall, Jackson and Mullarkey's (1995) reliability and validity testing of measures for job characteristics and cognitive demand in the workplace. The scale was intended to test the need for "the more active cognitive processing requirements of a job" (p.433) and for 'problem analysability.' This is consistent with the frequent requirement for maintenance technician to diagnose problems outside of their routine maintenance activities and develop appropriate solutions. The *Problem-solving* scale is able to assess the perception of maintainers that jobs arise that do not have a unique or obvious solution. A lack of obvious or routine solution is the type of situation in which assumptions are more likely to be made in order to proceed with a task. From the structured interviews, it emerged that tasks with characteristics that were unusual or outside expected routines were more likely to lead to faulty assumptions, as solutions were often identified based solely on past experiences. For these reasons, the *Problem-solving* scale was included in Study 3.

The second dimension of *Assumption* relates to the person's inclination to obtain systematically any needed information, as opposed to relying on assumptions when deciding how to proceed. Work motivation theory (Latham & Pinder, 2005) attributed this partly to personality traits, particularly conscientiousness, and partly to other considerations, including job design and learning context, which influenced the effort applied to solving complex tasks. Janis and Mann (1977) developed the Conflict Theory of Decision-making, a model of several psychological dimensions of decision-making, including conscientiousness in decision-making, which they termed 'vigilance'. These aspects of vigilance in decision-making were incorporated into the Melbourne Decision-Making Questionnaire by Mann, Burnett, Radford, and Ford (1997). Their *Vigilance* scale captures the traits of a person in terms of how methodical they perceive themselves to be when proceeding with solving job-related problems and making required decisions. In their description of *Vigilance,* they explained that:

> The decision-maker clarifies objectives to be achieved by the decision, canvasses an array of alternatives, searches painstakingly for relevant information, assimilates information in an unbiased manner, and evaluates alternatives carefully before making a choice...According to the conflict model, vigilance is the only coping pattern that allows sound and rational decision-making. (p.2)

The *Vigilance* scale is therefore also relevant to the cases relating to *Assumption* reported in the interviews in Study 2 and was selected as a measure for Study 3. The other scales in the Melbourne Decision-Making Questionnaire, such as *Buck-passing* and *Procrastination,* as well as measures in other studies relating to decision-making (see Section 2.9.4) did not appear to measure the constructs implicit in *Assumption*.

7.1.2.2 Design & Maintenance

The HFIT code *Design & Maintenance* included issues relating to adequate engineering of equipment and parts, problems encountered with modifications, and a lack of maintenance of equipment (see Section 5.3). Responses in the interviews in Study 2 relating to *Maintainability* of equipment included the difficulty of accessing components for maintenance due to space limitations or location height, and unfamiliarity with equipment due to a lack of standardisation in the design of units in the plant. Poor labelling of units was particularly an issue for Instrumentation/ Electricians (Inlecs), when unexpected interconnections resulted in shutdown of the plant.

The review of published literature indicated that a number of constructs are in use to define the relationship between maintainers' tasks and equipment design. The constructs commonly discussed in relation to engineering design included *Maintainability* and *Usability*. Both of these constructs offered only a limited basis for measuring the dimensions that were identified in Study 2.

Maintainability, as discussed in engineering literature (e.g., Wani & Gandhi, 1999) refers to the ease with which maintenance tasks can be carried out on a specific piece of equipment. The relevant International Standards Organization standard (2006a) defined *Maintainability* as "the ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources" (p.15). A commonly accepted measure of *Maintainability* (Mason, 1990) is the Bretby Maintainability Index. The Bretby Maintainability Index considers parameters such as the weight of machines, how easily cover plates can be removed, and how difficult it is to access internal components. This measure is intended to quantify the ease with which a specific item of machinery can be maintained. It does not elicit the perceptions of maintainers with regard to their daily interaction with an entire plant. As the Bretby Maintainability Index was designed as an assessment guideline for maintenance engineers and not as a means of surveying maintenance technicians, it was considered unsuitable for use in Study 3.

Alternatively, various measures of *Usability* consider the impact of system design on ease of use (International Standards Organization, 1998). The measures available are typically intended for assessing computer-based systems such as the *System Usability Scale* (Brooke, 1996). The *System Usability Scale* considers such factors as consistency of a system, whether a system is unnecessarily complex, and whether the support of a technical person is required to deal with problems encountered. 'Ease of use' is an important concept in conducting maintenance tasks. However, because of the specificity of the scale to using a specific device such as a computer, it did not appear to be suitable for assessing the ease of maintaining a complex process plant. Investigation of other literature discussing usability did not reveal an alternative scale that was suitable for measuring the ease of maintaining plant and equipment.

The intent, based on the results of Study 2 and the objective of Study 3, was to select an appropriate instrument to measure the perceived suitability of equipment and components for their function, and the influence of plant design on ease of conducting maintenance activities. Given the apparent lack of a suitable measure in the published literature, a scale was constructed for Study 3 based on the most-frequent *Design & Maintenance* sub-factors from Study 2 (see Section 5.3.3, Table 10). Scale items were constructed from the questions in HFIT, with re-wording to reflect the intent to measure perceptions relating to the plant in general, and not a specific part or failure. For example, the question in HFIT (Gordon, 2001) relating to equipment labelling asks, "Is the equipment involved in this incident labelled adequately" (p.53). This question was revised for the survey to, "Do you find that equipment is accurately labelled for maintenance work?" (Question 8).

7.1.2.3 Communication

The code in HFIT named *Communication* consisted of a number of questions relating to job-related and organisational communication. The most frequently-reported sub-factor of *Communication* in Study 2 was *Lack of Communication*, i.e. that the failure occurred in part because communication that was relevant to the maintenance job did not occur (see Section 5.3). The second and third most common sub-factors referred to the locus of the communication lapses, for example if there was insufficient communication between on-shore and offshore personnel (typically between maintenance technicians and engineers or planners) or between the company and a contractor, vendor, or agent involved in the work.

The organisational impediments to communication identified in Study 2 and discussed in Section 5.4.4 included:

- A general reluctance to communicate with maintenance personnel, often on the part of on-shore engineers. One interviewee commented that the "System did not promote communication between parts inspectors and the [off-shore] end-user."
- A reluctance to take the time to record or pass on useful information, particularly when this required up-dating electronic IM systems.
- Weak communication links between involved parties, as in the case of vendors suppling equipment without advising of important changes made to equipment, or difficulties of communicating the nature of problems to engineers on-shore.
- Information entered into work order notifications and other databases not being seen due to poor placement on computer screens (e.g., important text located at the bottom of a screen).
- The large proportion of task-related information being supplied from electronic databases, which tended to inhibit any required clarification and discussion.

Based on these dysfunctions, the scale selected to measure organisational communication was required to capture perceptions about the flow of information through the organisation, the ease of using existing communication channels to obtain information, and the effectiveness of obtaining information from relevant parties to a maintenance task, including engineers, supervisors, planners, and vendors.

Several organisational communication questionnaires were examined to determine if they offered a suitable measurement scale to test for the impediments to job-related communication as outlined above. After reviewing a number of communication measures (Greenbaum, Clampitt, & Willihnganz, 1988; Rubin, Palmgreen, & Sypher, 2004) three measures were found to be of particular relevance:

- Organizational Communication Development Audit Questionnaire (OCD) developed by Wiio (1978a; 1978b).

- Organizational Communication Scale (OCS) developed by Roberts and O'Reilly (1974)
- Communication Satisfaction Questionnaire (CSQ) developed by Downs and Hazen (1977).

The main focus of the Organizational Communication Scale is on the quality of communication between the employee and the supervisor. This includes many aspects of employment unrelated to the performance of required work, such as trust in the supervisor, career prospects, and reluctance to communicate information to others. Similarly, the Communication Satisfaction Questionnaire is mainly concerned with examining inter-personal communication in the workplace, including such issues as trust, conflict, and motivation. From the interviews, there was no indication that impediments to obtaining information originated from any of these dimensions of personal interactions. While these are important issues in organisational communication, the difficulties for maintenance technicians appeared to stem from a variety of obstacles to information transfer from the various sources from which work-related information was generally acquired. In contrast to the other instruments, the Organizational Communication Development Audit Questionnaire has items relating to overall satisfaction with the availability of information, as well as how much information is obtained from specific sources and the amount of work-related information received. Downs (2004) commented, "The OCD Audit Questionnaire is one of the most thoroughly worked out instruments for organizations" (p. 248). Therefore, the OCD was deemed able to measure the characteristics of organisational communication alluded to in the interviews, and therefore the most suitable source for a communication scale for the Study 3 survey.

The OCD was developed at the Research Institute for Business Economics (LTT) in Helsinki based on the original LTT Communication Audit (Wiio and Helsila, 1974). Wiio (1978a) then incorporated his Workshop Delphi procedure for auditing organisational communication, thereby creating two versions of the OCD, named OCD/1 and OCD/2. In OCD/1, the Workshop Delphi auditing approach involves holding discussions with workgroups to identify organisational problems, and then developing a survey questionnaire based on the issues arising from these discussions (Greenbaum, Clampitt, & Willihnganz, 1988). Study 3 in the current research used a similar approach to OCD/1, in which interviews were used to identify the main problem areas, followed by a survey to obtain a more detailed understanding of the perceptions of participants. Wiio (1978b) later refined and standardised the questionnaire to produce OCD/2, which uses 12 scales and 76 items to examine organisational communication. Also included is a matrix of *Topics of Information* and *Sources of Information* with a request for the participant to nominate his or her preferred source for each topic. The questionnaire results are presented to the organisation, and in turn provide the basis for conducting an OCD/1 Workshop Delphi audit (Greenbaum, Clampitt, & Willihnganz, 1988). The standardised OCD/2 audit questionnaire was used for the *Organisational Communication* scales in the Study 3 survey.

7.1.3 Objective and hypotheses of Study 3

The objective of Study 3 was to determine if higher and lower reliability work areas in the target organisation could be differentiated on the basis of perceptions of maintenance personnel concerning the human factors identified in Study 2. The organisation has three types of facility (Gas Platforms, FPSOs, and the Gas Process Plant), and has access to personnel in three sites for each facility type.

The specific hypotheses tested were:

- H_1: There is a significant difference in the perception of *Problem-solving* between higher, middle, and lower reliability work areas, across all facility types, with more reliable work areas showing higher scores on *Problem-solving*.
- H_2: There is a significant difference in the perception of *Vigilance* between higher, middle, and lower reliability work areas across all facility types, with more reliable work areas showing higher scores on *Vigilance*.
- H_3: There is a significant difference in the perception of *Design & Maintenance* between higher, middle, and lower reliability work areas, across all facility types, with more reliable work areas showing higher scores on *Design & Maintenance*.
- H_4: There is a significant difference in the perception of *Organisational Communication* between higher, middle, and lower reliability work areas,

across all facility types, with more reliable work areas showing higher scores on *Organisational Communication*.

7.2 Method

7.2.1 Experimental design

The study utilised a 3x3 independent group design with *Reliability* (higher, middle, and lower) and *Facility Type* (FPSO, Gas Platform, and Process Plant) as independent variables (IVs), and *Problem-solving, Vigilance, Design & Maintenance*, and *Organisational Communication* as the dependent variables (DVs).

7.2.2 Participants

Participants were recruited from the following nine work locations:

- The three existing Floating Production, Storage and Offloading (FPSO) facilities;
- The three off-shore gas platforms that were operating at the start of the research.
- Three distinct maintenance areas identified in the Gas Process Plant;

All maintenance personnel (N=428), including maintenance technicians, coordinator/planners, and supervisors from the nine identified work areas were invited to participate. At the request of the organisation, age and gender data was not collected, but organisational records showed that 97.0% of the production workforce was male, the range of ages was 22 to 66 years with a mean age of 42.3 years, and the mean time with the company was 6.6 years. From the questionnaires distributed, 178 completed forms were received, a response rate of 41.6%.

7.2.3 Measures

7.2.3.1 Problem-solving

Problem-solving was measured using the *Problem-solving* scale in Morgeson and Humphrey's (2006) Work Design Questionnaire (see Appendix E for a copy of this and other scales used in the study). An example of an item in the scale is, "The job involves solving problems that have no obvious correct answer" (p.1338). The response scale is: 0) Strongly Disagree 1) Disagree 2) Hard to Say 3) Agree 4) Strongly Agree.

Convergent validity was demonstrated by Morgeson and Humphrey (2006) through convergence of their data with previously gathered information relating to job characteristics in the Occupational Information Network (O*NET) job database created by the U.S. Department of Labor (Peterson et al., 2001). Discriminant validity of the WDQ was demonstrated by the ability to discriminate between occupational categories in O*NET on the basis of the scales in the WDQ. They considered that construct validity was justified on the basis that the job characteristics expected in professional and non-professional job categories were differentiated by the data obtained using the WDQ. The internal reliability coefficient for the *Problem-solving* scale was found to be α=0.84 (Morgeson & Humphrey, 2006).

7.2.3.2 Vigilance

Vigilance was measured using the *Vigilance* scale in the Melbourne Decision-Making Questionnaire (Mann, Burnett, Radford, & Ford, 1997). An example of an item in the *Vigilance* scale (Appendix E) is, "When making decisions I like to collect a lot of information." The response scale for the statements in the scale is: 0) Strongly Disagree 1) Disagree 2) Hard to Say 3) Agree 4) Strongly Agree.

Mann et al considered that testing of the original Flinders DMQ confirmed the validity of *Vigilance* as one of the mechanisms of decision-making in their model based on Conflict Theory. They conducted Confirmatory Factor Analysis on the scale items in order to revise the original Flinders Decision-Making Questionnaire. In a large study using the Melbourne Decision-Making Questionnaire (n=2018) the internal reliability for the *Vigilance* scale was found to be α= 0.80.

7.2.3.3 Design & Maintenance

Scale items for *Design & Maintenance* were constructed by re-wording the questions in HFIT to assess perceptions of maintenance personnel concerning the design and maintainability of their work area in general. HFIT was validated in the context of a procedure for investigating incidents, as outlined in Section 4.2.2. The inter-rater reliability (r_{wg} =1) of the original factor in HFIT was based on all of the raters agreeing that the factor was not present in the accidents that they reviewed (Gordon, Flin, & Mearns, 2005). Given that the *Design & Maintenance* scale has been constructed for Study 3, its construct validity was assessed through an Exploratory Factor Analysis prior to its use in testing group differences. The response scale for the questions regarding the *Design & Maintenance* scale were: 0) Never 1) Hardly Ever 2) Sometimes 3) Often 4) Always. Questions 4-6 in this scale were reverse-coded.

7.2.3.4 Organisational communication

The OCD/2 questionnaire was designed to measure the quality of work-related information from specific sources and on specific subjects. The OCD/2 consists of 12 scales concerning aspects of organisational communication and job satisfaction. Two scales were selected (Appendix E) from the OCD/2: 1) *Amount of information from different sources* and 2) *Amount of information about different subjects* (Wiio, 1978a, p. 116).

The OCD/2 scale concerning sources of information was selected because reports in Study 2 frequently mentioned poor communication from specific sources (e.g. engineers, vendors, procedures, and computer based sources). This scale of the OCD/2 allows for one organisation-specific source, and this was assigned to 'vendors' as they were specifically mentioned in the interviews as not providing sufficient information at times. Four of the six items from the scale *Amount of information from different sources* refer to feed-back required for the person's job. For example, one question asks, "How much information about your work do you get now from: Your Supervisor?" The remaining items refer to sources of task-related information.

The OCD/2 scale concerning subjects of information was selected as a number of failures in Study 2 related to information about workplace and task-related changes that were not communicated to the person, such as changes to equipment, connections, and procedures. As an example, one of the five questions asks, "What is the amount of information you receive now about the following job items: Changes in procedures/New procedures." These two communication scales concerning sources of information and subjects of information had the response scale: 0) Very Little 1) Little 2) Hard to Say 3) Much 4) Very Much.

In addition to the 12 scales mentioned, the OCD/2 also has a 'global question' for testing overall satisfaction with communication and information availability. This item from the OCD that asks, "Are you satisfied or dissatisfied with communication and the availability of information in your organization?" was also included in the survey. The response scale for this question was: 0) Very Dissatisfied 1) Dissatisfied 2) Hard to Say 3) Satisfied 4) Very Satisfied.

Validity and reliability assessments for the OCD/2 were included in the reviews mentioned above. Greenbaum, Clampitt, and Willihnganz (1988) reported that reliability levels were determined for the LTT Organisational Communication Audit Questionnaire, the original version of the OCD/2. Cronbach's alpha was very high (α=0.97) across 58 items in the LTT. Test-retest reliability was not measured. However, Aberg (1986) used the Source-to-Item Matrix of the OCD/2 to measure information seeking and communication structure patterns across 18 organisations in Finland. He concluded that the significant correlations between OCD/2 measures of frequency of use of a particular information source and the perceived informativeness within the data from two companies, confirmed the criterion validity of the OCD/2.

Greenbaum, Clampitt, and Willihnganz (1988) report that, as well as having high face validity, Wiio has used a number of methods to prove the construct validity of the questionnaire. These included Factor Analysis (four factors accounted for 28% of the variance) and regression analysis (25 variables in the survey accounted for 38% of the variance). They also reported that while only Wiio's research using the OCD/2 has been published in English, the OCD/2 has been used by other researchers in the United States and Australia.

Downs (2004) also reviewed the OCD/2 and concluded that available reliability and validity data applied mainly to the LTT Communication Audit. He also commented that "What is not clear, however, is how the OCD version was generated from the LTT" (p.248). However, despite the uncertainty concerning validity of the scale structure, he considered that due to its thorough development, extensive use across different organisations, and the refinements applied based on experience, the OCD/2 provided a "simple way of obtaining a lot of data about the organization" (p. 249).

As the reviews above indicated a degree of ambiguity in the scale structure of the OCD/2, an Exploratory Factor Analysis was conducted to test the structure of the factors in the communication scales before they were used to test the research hypotheses.

7.2.3.6 Demographics

The following demographic information was also measured:

- Usual workplace (facility and work area)
- Workgroup type (Core Crew, Shutdown Crew, or Major Maintenance)
- Work category (Inlec/electrical or mechanical)
- Length of time at their facility
- Total time in the resource industry
- Employing company (target company or contractor).

In addition, space was provided for a response to an open-ended request for further information, "Please write any comments you have on what helps or gets in the way of maintenance work at [the company]." An open-ended question was included to elicit the respondent's perceptions of either the topics covered in the questionnaire, or topics that were not anticipated in the design of the questionnaire, but were considered by the participant to be relevant to his or her work (Chalton & O'Brien, 2002). A copy of the final form of the survey can be found in Appendix F.

7.2.4 Procedure

Ethical approval for the project was obtained (Appendix B) from the Human Research Ethics Committee of Curtin University of Technology (Approval number HR 147/2007). Surveys and addressed reply-paid envelopes were sent to maintenance coordinators at each of the surveyed work areas. A total of 373 surveys were sent by internal mail to maintenance coordinators for distribution. An additional 55 surveys were printed and distributed on one of the FPSOs. As a follow-up to the initial mail-out, an email message was sent to all identifiable maintenance personnel. Respondents placed completed survey forms into individual envelopes and returned them to the researcher via the company's internal mail system.

7.3 Results

7.3.1 Data screening

SPSS Version 17.0 (SPSS Inc., Chicago, USA) was used to analyse the data collected. The numeric values of the Likert scales on the questionnaire ranged from *0* to *4* and these were recoded into the dataset in the range *1* to *5*, in keeping with SPSS convention. The data from the comments sections were entered into a Microsoft Excel spreadsheet for qualitative analysis in order to triangulate the data obtained from the quantitative analysis of item responses. The qualitative analyses will be presented in Chapter 8.

Of the 178 returned surveys, six were eliminated on the basis of having more than 10% missing values. Of the remaining surveys, three had two missing data points (6.6% missing values), and six had one missing data point (3.3% missing). No particular pattern was apparent in the missing data, and so the missing values were determined to be 'missing at random' (Tabachnick & Fidell, 2007). The missing values were replaced by the series mean for that question (Allen & Bennett, 2008). A total of 172 valid surveys were retained for analysis.

The maximum number of missing data points for a particular question was five (2.9% missing) for Question 22 ("How much information do you now get from staff meetings"), which was not sufficient to justify eliminating it from the analysis as a variable.

On five surveys there were multiple responses to at least one of the questions. All five were examined and showed a clear intention (e.g., one response was only half circled, or one response was an outlier in a series of similar responses) and therefore these values were entered. The returned surveys were then examined for response sets. Many of the surveys contained a series of similar responses, particularly in the *Vigilance* scale and the OCD-*Sources of Information* scale. However, after examining the remaining scales, a diversity of answers to other questions was taken as an indication that the respondent had considered the questions, and had arrived at the same response for these particular questions.

7.3.2 Descriptive statistics

7.3.2.1 Demographics of respondents

Table 12 shows the frequency of responses across the nine work areas and the response rate by facility. The Process Plant and gas platforms were equally represented, while the FPSOs were slightly under-represented. A number of respondents indicated that they worked in more than one work area. Thirty-nine respondents indicated that they worked across all areas of the Process Plant, and five respondents marked two of the gas platforms as their work areas. These 44 respondents were included in the scale validity tests, but omitted from the between-groups analyses. Due to the high number of personnel working across all areas of the Process Plant, only the overall response rate for the plant could be estimated. In addition, the number of responses specifically from Process Plant 1 and Process Plant 2 was low due the number of respondents from these areas who work in other areas as well.

Table 12. Frequency of survey responses and response rate for off-shore facilities and Process Plant work areas.

Facility/Work Area	Number of Responses Received	Response Rate (%)
Gas Platform 1 (GP1)	23	57.5
Gas Platform 2 (GP2)	22	36.7
Gas Platform 3 (GP3)	3	15.0
Gas Platform 1 and 2 (GP1+2)	5	
FPSO 1 (FP1)	12	22.9
FPSO 2 (FP2)	21	38.2
FPSO 3 (FP3)	21	52.2
Process Plant (Overall)	70	46.7
Process Plant 1 (PP1)	8	N/A
Process Plant 2 (PP2)	6	N/A
Process Plant 3 (PP3)	17	N/A
Process Plant (All Areas)	39	N/A

The distribution of respondents by work category (Figure 8) indicated a higher proportion of mechanical maintenance personnel than Inlec/electrical, reflecting the greater numbers of mechanical maintainers employed by the company. The response from the different work areas was relatively consistent, with the exception of FPSO 3, in which mechanical maintainers were over-represented.

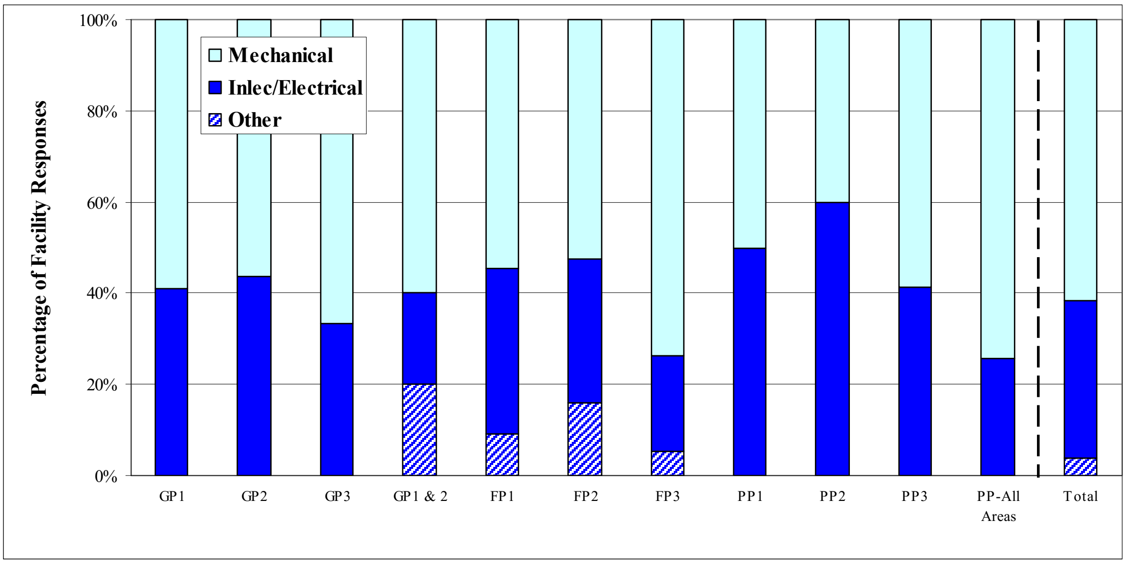

Figure 8. Frequency distribution of respondents by work category.

The distribution of respondents by work group type (Figure 9) indicated that most respondents (68.6%) worked in the Core Crews based at the facilities, rather than in the Major Maintenance (16.3%) and Shutdown Crews (6.4%) that are based at head office and sent to the facilities as required. A high proportion of the Major Maintenance cohort worked in the Process Plant-All Areas (67.9%) and FPSO 1 (17.9%).

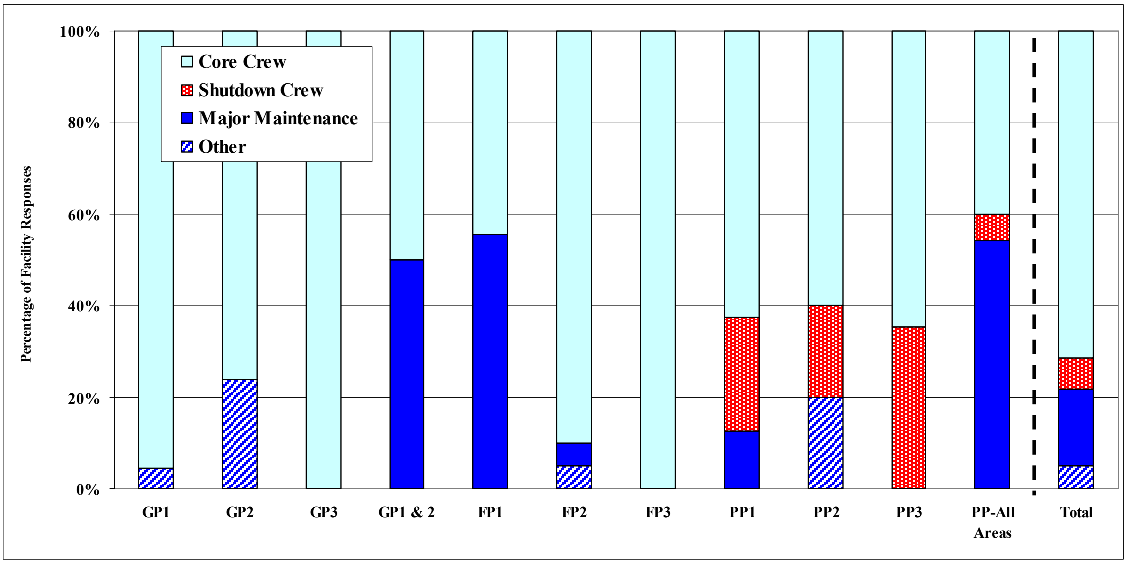

Figure 9. Distribution of respondents by work group type.

The frequency of responses by employer (Figure 10) indicated that 65.7% of respondents were employed by the target company, and 34.3% of were employed by outside contractors. Of the contractors, most were working in Gas Platform 2 (19%) and Process Plant-All Areas (60.3%). Of the respondents from Process Plant-All Areas, 94.6% were contractors.

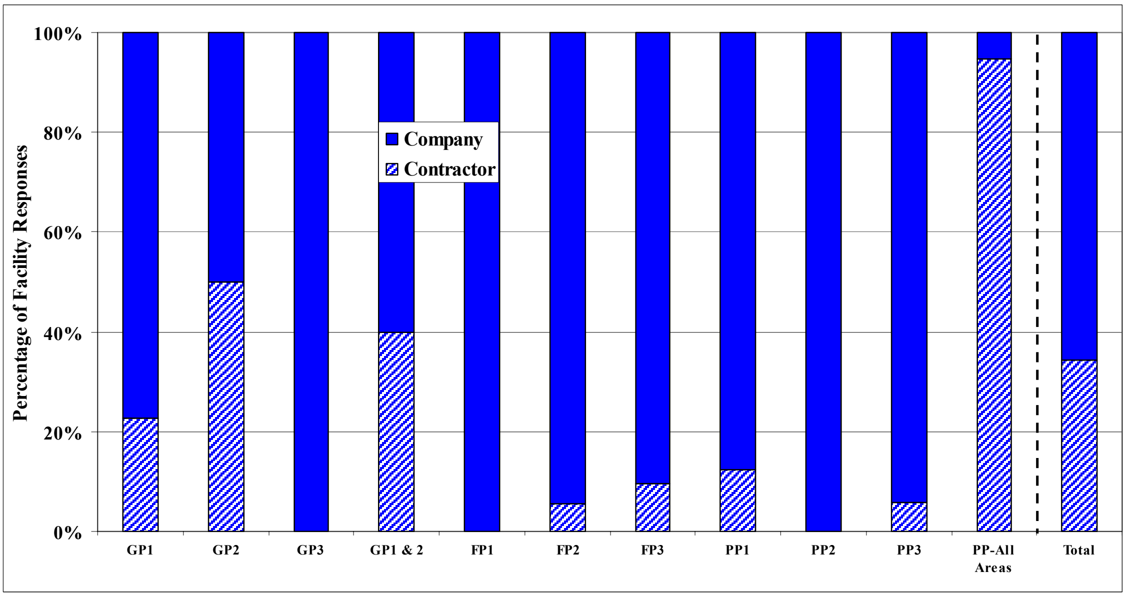

Figure 10. Frequency of responses by employer.

Figure 11 shows the distribution of respondents' time worked at their current facility. Most respondents (36.0%) had worked at their facility for 3-10 years, with 17.6% working there for over 10 years and 2.9% under 3 months.

Similarly, the frequency of responses by tenure in the resource industry (Figure 12) indicated long service times in the industry. Most respondents (61%) had worked in the industry for over 10 years, with 28.5% working there for 3- 10 years and relatively few (0.6%) under 3 months.

Apart from the exceptions noted above, the respondents to the survey generally formed a representative sample of the population of maintenance personnel across the target organisation.

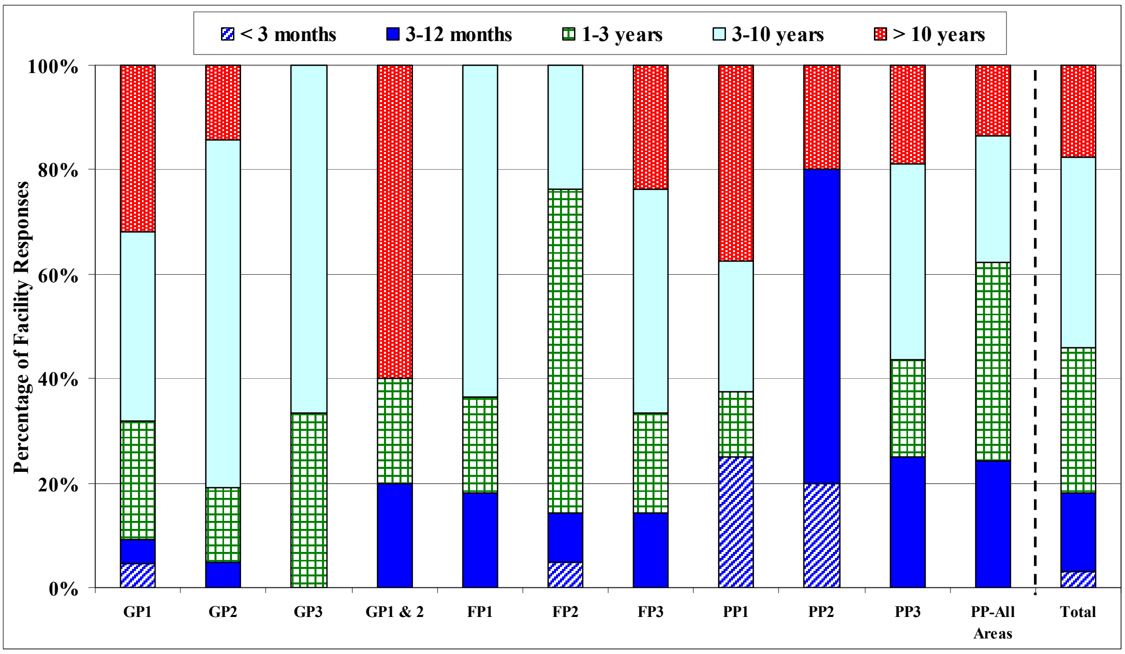

Figure 11. Frequency of the respondents' time at their facility.

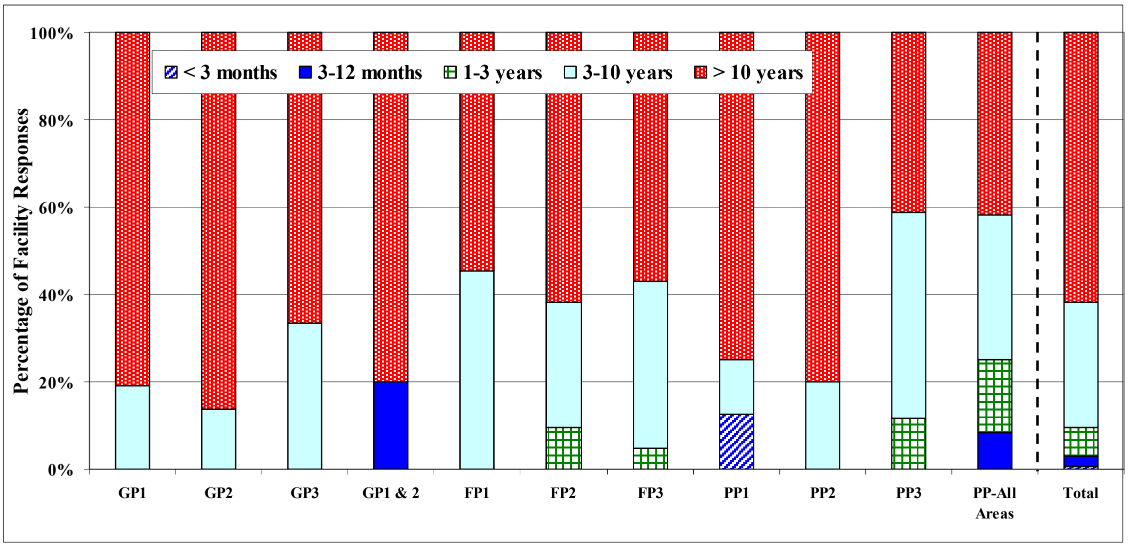

Figure 12. Frequency of respondents' time in the resource industry.

7.3.3 Factor validity

The *Design & Maintenance* section had been developed from HFIT and therefore the factor structure needed testing to ensure that the scale was uni-dimensional and internally consistent. An Exploratory Factor Analysis was conducted on the dataset of responses to identify the underlying factor structure. The *Organisational Communication* scales of the survey were constructed from the previously developed and validated scales of the OCD/2. However, due to ambiguity described in the literature relating to the factor structure of the OCD/2, relative to the earlier LTT Communication Audit, it was considered that an Exploratory Factor Analysis of the OCD/2 was also advisable.

The *Design & Maintenance* and *Organisational Communication* items in the screened dataset were subjected to two separate Factor Analyses. Principal Axis Factoring (PAF) was applied as there were expected to be theoretical as well as empirical associations between variables. Although a sample size of 300 is considered "comforting" by Tabachnick and Fidell (2007, p.613), they advised that a sample of 150 would be sufficient if loadings were high (>.80), particularly on so-called 'marker variables'. The sample size (N= 172) met their criterion for factorability, though the occurrence of many cross-factor loadings meant that most loadings did not satisfy their recommendation. Another requirement for Factor Analysis is independence of measurements. Questionnaires were completed independently and therefore fulfil this requirement. Testing of the assumptions of normality, linearity and multicollinearity, and assessment of factorability criteria, are provided for the *Design & Maintenance* scale in Appendix G, and for the *Organisational Communication* scales in Appendix H. As indicated, several violations of these assumptions were encountered in the dataset, but Factor Analysis is considered robust with regard to violations of these assumptions (Allen & Bennett, 2008).

The results of the respective Exploratory Factor Analyses are also provided in these appendices. Appendix G provides the results of PAF with Varimax Rotation conducted on the *Design & Maintenance* items. The analysis showed that two factors had Eigenvalues above 1.0, but that there were significant cross-loadings of items onto both factors. A one-factor solution provided the best internal reliability (Cronbach's α=.729), as reliability decreased with the removal of any item. Therefore, a decision was made to treat the *Design & Maintenance* scale as measuring a single variable for the purposes of further analyses. The total variance explained by this variable was 34.8%.

Appendix H provides the results of PAF with Varimax Rotation conducted on the items in the communication section of the survey. Factor Analysis revealed a four-factor solution; however some items loaded onto multiple factors or none of the factors. Removal of these items suggested a two-factor solution. The first factor (Items 19, 20, 22 and 26) pertained to information from either the organisation or the person's supervisor about his or her work, and was named *Job-related feedback*. The total variance explained by this variable was 15.3%. The second factor was derived from items 27-30. As these items pertained to the amount of information received concerning organisational changes, it was named *Information about change*. The total variance explained by this variable was 14.5%.

7.3.3.1 Descriptive statistics for the dependent variables

Descriptive statistics were derived from the recoded dataset of 172 valid questionnaires. Statistical values were calculated for each scale (Table 13). The scoring range for all items was from 1 (most negative) to 5 (most positive). Values for mean and skewness were highest for items in the *Vigilance* scale, indicating a tendency to more positive self-reports regarding the person's approach to analysing tasks. Means were lowest, with relatively high standard deviations, for *Information about change* and *Problem-solving*.

Table 13. Descriptive Statistics for variable means from the survey results[a].

Variable Name	Min.	Max.	Mean	S.D.	Skewness	Kurtosis
Problem-solving	1.50	4.75	3.04	.63	.10	-.56
Vigilance	3.17	5.00	4.15	.38	.43	.15
Design & Maintenance[b]	1.88	4.50	3.38	.42	-.11	.77
Job-related feedback	1.00	5.00	3.24	.74	-.27	.05
Information about change	1.25	5.00	3.03	.75	.17	-.31

[a] Possible range for all scales = 1 to 5
[b] Scale for this variable includes reverse-coded items.

Table 14 shows the means and standard deviations for each scale in each of the nine work areas. *Vigilance* was found to be consistently high among all work areas, while the *Organisational Communication* scales (*Information about change* and *Job-related feedback*) were lower in the Process Plant.

Table 14. Variable means (standard deviations) arranged by facility.

	Problem-solving		*Vigilance*		*Design & Maintenance*		*Job-related feedback*		*Information about change*	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
GP1	3.06	(.61)	4.23	(.45)	3.34	(.51)	3.26	(.67)	3.12	(.66)
GP2	3.10	(.58)	4.10	(.40)	3.39	(.39)	3.44	(.63)	3.00	(.58)
GP3	3.08	(.63)	4.22	(.69)	3.25	(.38)	3.00	(.66)	3.42	(1.23)
FP1	3.09	(.70)	4.30	(.45)	3.70	(.32)	3.34	(.53)	3.23	(.68)
FP2	2.87	(.54)	4.19	(.42)	3.58	(.33)	3.17	(.99)	3.29	(.96)
FP3	3.40	(.64)	4.18	(.42)	3.17	(.51)	3.18	(.82)	3.12	(.58)
PP1	2.91	(.76)	4.15	(.38)	3.31	(.31)	3.00	(.85)	2.75	(.64)
PP2	2.90	(.34)	4.17	(.37)	3.30	(.26)	2.95	(.60)	2.85	(.58)
PP3	3.13	(.67)	4.14	(.32)	3.34	(.26)	2.75	(.80)	2.66	(.83)
PP-All Areas	2.94	(.60)	4.07	(.29)	3.41	(.45)	3.52	(.59)	2.96	(.81)

Table 15 shows the correlation matrix for the five dependent variables derived from the survey data, and the demographic variables *Time at Facility, Time in Industry,* and *Employer*. *Time at Facility* showed a significant negative correlation with *Design & Maintenance*. *Employer* showed a positive correlation with *Job-related* *feedback*. These significant correlations between demographic variables and the independent variables in the study indicate that the demographic variables should be treated as covariates in the relevant analyses.

Table 15. Correlation matrix for the five dependent variables and three demographic variables in the final factor structure.

	PS	V	D&M	JRF	IAC	TaF	TiI	Emp
Problem-solving	*.675*	-		-	-	-	-	-
Vigilance	.044	*.785*		-	-	-	-	-
Design & Maintenance	-.358**	.159*	*.729*					
Job-related feedback	.013	.176*	.327**	*.742*	-	-	-	-
Information about change	-.089	.192*	.344**	.500**	*.724*	-	-	-
Time at Facility	-.056	-.022	-.199**	-.092	.007		-	-
Time in Industry	-.038	.017	-.084	-.125	.015	.404**		-
Employer	-.056	-.076	.166	.371**	.096	-.155*	-.231**	

Cronbach's α for each scale are shown on the diagonal
** Correlation was significant at the 0.01 level
* Correlation was significant at the 0.05 level

7.3.4 Hypothesis testing

Between-group analyses were conducted to determine if significant differences existed between work areas. The planned analyses were a series of 3 x 3 (two-way) analyses of variance (ANOVA) with the independent variables based on a three-level ranking of reliability (lowest, middle, and highest) across three different facility types (FPSO, Gas Platform, and the Process Plant) using the dependent variables (DVs) derived from the survey measures. However, an insufficient or unequal number of returned questionnaires from several work areas (Table 12) meant that one of the gas platforms, and the Process Plant work areas could not be used for this analysis. The facilities with suitable numbers of completed questionnaires allowed 2 x 2 two-way ANOVAs (i.e., two reliability levels in FPSOs and gas platforms), and 1 x 3 one-way ANOVAs (i.e., three reliability levels across FPSOs), using each of the five measures as DVs.

In the two-way ANOVAs, the gas platforms Gas Platform 1 and Gas Platform 2 were used, as the number of responses from Gas Platform 3 was low (n=3). The FPSOs

FPSO 2 and FPSO 3 were selected for the two-way ANOVAs, as the numbers of responses were similar (n=21 for both), and higher than FPSO 1 (n=12). However, this meant that the medium and high reliability gas platforms were compared to the low and medium FPSOs. As the rankings were relative, and the facilities sufficiently different in operating characteristics, this was thought unlikely to compromise the analysis.

7.3.4.1 Problem-solving

A two-way Between-Groups ANOVA was used to compare the responses to the items in the problem-solving scale at two reliability levels (termed *Lower* and *Higher Reliability*) and for two facility types (FPSOs and gas platforms). A Shapiro-Wilk Test for normality and Levene's Test for the homogeneity of variance were conducted (Appendix I). The assumptions of normality and homogeneity were not violated.

The main effect of *Reliability Level* on *Problem-solving* was found to be significant $F(1,82)= 5.17$, $p=.026$, partial $\eta^2=.059$. Respondents from the lower reliability facilities expressed more agreement with items referring to requirements for *Problem-solving* than from higher reliability facilities (Figure 13). Partial η^2 indicated that *Reliability Level* accounted for 5.9% of variance, considered a medium effect size. The main effect of *Facility Type* was not significant, $F(1,82) = 3.194$, $p=.660$, partial $\eta^2 = .002$. The interaction between *Reliability Level* and *Facility Type* was just outside the 95% confidence limit, $F(1,82) = 3.69$, $p=.058$, partial $\eta^2 = .043$.

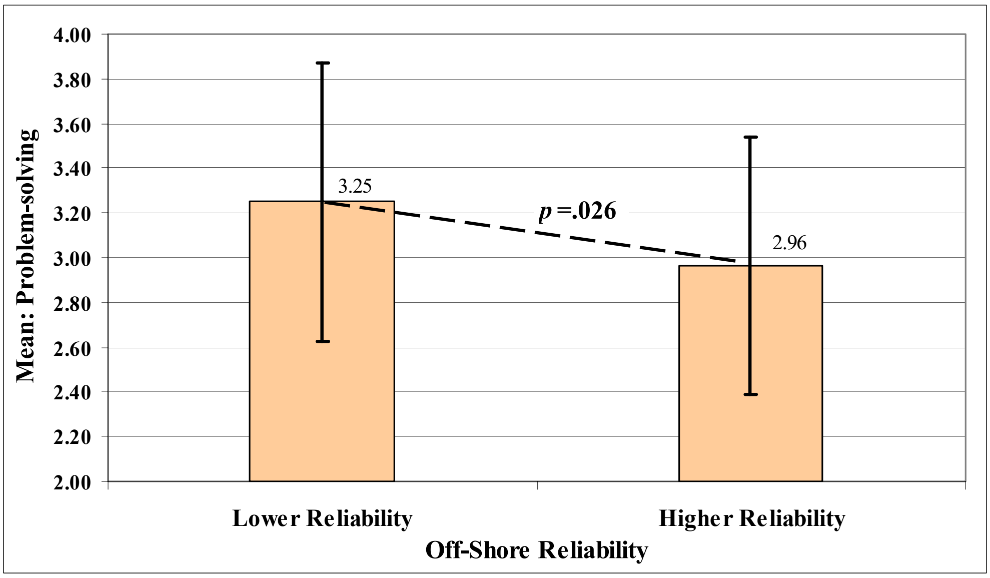

Figure 13. The effect of *Reliability Level* on scores for *Problem-solving*.

A one-way Between-Groups ANOVA was used to compare the responses to the items in the *Problem-solving* scale in FPSOs at three reliability levels. The assumptions of normality and homogeneity were not violated (Appendix I). A significant main effect from the ANOVA indicated that the three FPSOs differed on the *Problem-solving* scale, F (2,50) = 3.98, p=.025. Partial η^2 = .137 indicated that 13.7% of the variance in *Problem-solving* scores was due to *Reliability Level*. Post-hoc analyses using Tukey's Honestly Significant Difference (HSD) at α=.05 showed that the FPSO with the middle reliability level had significantly lower scores than the FPSO with the lowest reliability level (p=.019), but that with the highest reliability was not significantly different to either of the other facilities.

7.3.4.2 Vigilance

A two-way Between-Groups ANOVA was conducted to compare the responses to the items in the *Vigilance* scale at two reliability levels and for two facility types (FPSOs and gas platforms). The assumption of normality appeared to be violated (Appendix I) for the items in the *Vigilance* scale, as the Shapiro-Wilk Test returned a significant statistic (p<.05) for data from both lower and higher reliability facilities. Due to the sensitivity of the Shapiro-Wilk Test, a further test of normality was recommended (Allen & Bennett, 2008), which requires examining the skewness and kurtosis of the distribution. For all of the scale items, the skewness and kurtosis statistics were acceptable, i.e., between -1 and +1. A Levene's Test on the data returned a non-significant value, demonstrating that the assumption of homogeneity of variance was not violated.

The results of the two-way ANOVA showed no significant effect of *Reliability Level* on *Vigilance,* F (1,82) = .56, p=.457, partial η^2 = .007, and no significant effect of *Facility Type* on *Vigilance*, F (1,82) = .065, p=.799, partial η^2 = .001. In addition, no interaction effect between *Reliability Level* and *Facility Type* was observed, F (1,82) = .45, p=.504, partial η^2 = .005.

A one-way Between-Groups ANOVA was used to compare the responses to the items in the *Vigilance* scale in FPSOs at three reliability levels. The assumptions of normality and homogeneity were not violated (Appendix I). A non-significant result from the ANOVA indicated that there was no significant effect of *Reliability Level* on *Vigilance* in FPSOs, F (2,50) = .34, p=.717, partial η^2 = .013.

7.3.4.3 Design & Maintenance

A significant correlation was found (Table 15) between *Design & Maintenance* and *Time at Facility*. Between-groups Analyses of Covariance (ANCOVA) were therefore conducted using *Time at Facility* as a covariate to compare groups based on *Reliability Level* and *Facility Type*. Shapiro-Wilk Tests were conducted and found to support the assumption of normality, with the exception of data from FP1. However skewness and kurtosis data confirmed an approximately normal distribution, i.e., within the range -1 to +1. Levene's Tests confirmed that the assumption of homogeneity of variance was not violated. In addition, the assumption of linearity between the covariate and the dependent variable was tested using a graphical analysis technique recommended by Allen and Bennett (2008, pp. 130-132). Linearity was observed between *Design & Maintenance* and *Time at Facility* in a scatterplot (Figure 24). Testing for homogeneity of regression slopes (Appendix I) is an additional assumption test for ANCOVAs. The results of the test showed a non-significant interaction between *Reliability Level* (IV) and *Time at Facility* (covariate) in the two-way data, indicating that this assumption was not violated. However, the assumption was violated in the one-way data. Care is therefore recommended (Allen and Bennett, 2008) when interpreting the results of the one-way ANCOVA.

A two-way ANCOVA was conducted to compare the effect of *Reliability Level* and *Facility Type* on *Design & Maintenance* scores. *Time at Facility* was included as the covariate to control for the effect of the length of time that the respondent spent at his or her facility. The ANCOVA indicated that *Reliability Level* was not found to have a significant main effect on *Design & Maintenance,* $F(1, 80)=2.371$ $p=.128$, partial $\eta^2=.029$. *Time at Facility* was also not found to be significantly related to *Design & Maintenance,* $F(1, 80)=.578$, $p=.449$, partial $\eta^2=.007$. However, there was a significant interaction between *Reliability Level* and *Facility Type*, $F(1, 80)=4.973$ $p=.029$, partial $\eta^2=.059$, a medium effect size. Consequently, simple effects analyses were conducted to investigate this interaction. The analyses showed that respondent's agreement with *Design & Maintenance* items increased significantly with higher *Reliability Level* on FPSOs, $F(1, 80)=48.11$ $p<.01$, but not on gas platforms, $F(1, 80)=.116$, *ns.*

A one-way ANCOVA was conducted to compare the effect of *Reliability Level* among FPSOs on *Design & Maintenance* scores, with *Time at Facility* as a covariate. After controlling for the *Time at Facility*, *Reliability Level* for FPSOs was found to have a significant effect on perceptions of *Design & Maintenance,* $F(2, 49)=6.71$, $p=.003$, partial $\eta^2=.215$. *Reliability Level* accounted for 21.5% of the variance, a large effect size. Post hoc analyses conducted on pairs of FPSO work areas indicated that the scores for *Design & Maintenance* from the lowest and highest reliability work areas were significantly different, and from the lowest and middle reliability work areas were just out of the 95% confidence interval (Figure 14). The difference in scores between middle and highest reliability FPSO work areas was not significant.

Despite the violation of the assumption of homogeneity of regression slopes, the results for the one-way ANCOVA were supported by the two-way ANCOVA, namely that there is a significant effect of *Reliability Level* on *Design & Maintenance* for the FPSOs.

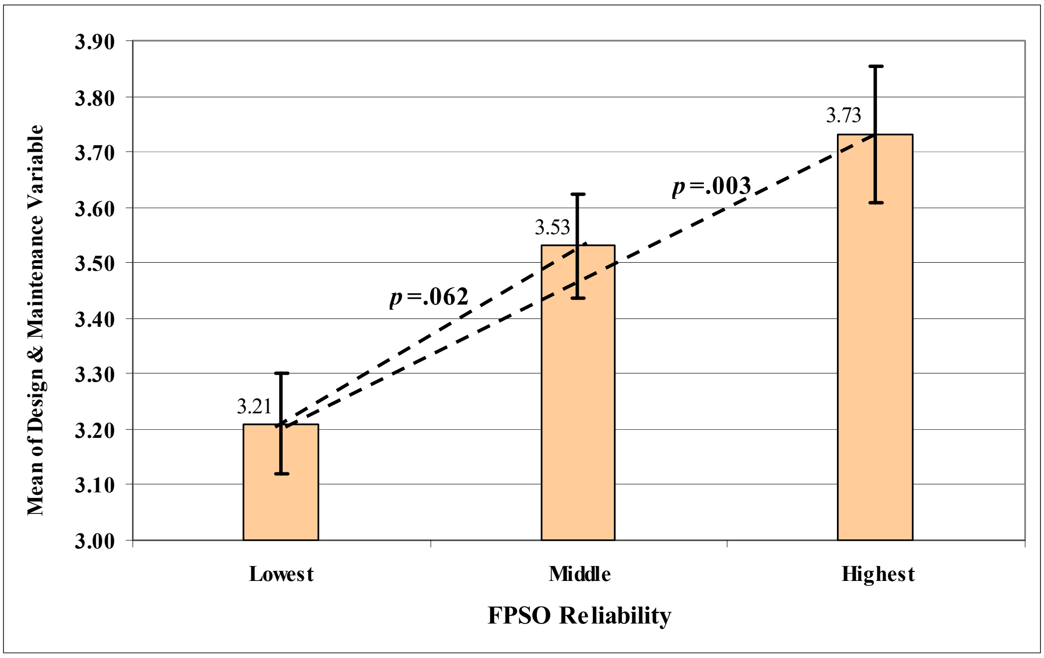

Figure 14. Effect of FPSO reliability level on reliability work areas *Design & Maintenance.* ANCOVA was evaluated at *Time at Facility*= .49.

7.3.4.4 Job-related feedback

A significant correlation was found (Table 15) between *Job-related Feedback* and *Employer*. Figure 15 shows the relationship between *Employer* and *Job-related feedback* for facilities in the analysis. Between-groups Analyses of Covariance (ANCOVA) were therefore conducted using *Employer* as a covariate to compare groups based on *Reliability Level* and *Facility Type*. Shapiro-Wilk Tests were conducted and found to support the assumption of normality. Levene's Tests confirmed that the assumption of homogeneity of variance was not violated. In addition, the assumption of linearity between the covariate and the dependent variable was tested using a graphical analysis technique recommended by Allen and Bennett (2008, pp. 130-132). Linearity was assessed based on a scatterplot of *Job-related Feedback* and *Employer* in (Figure 25). The assumption of homogeneity of regression slopes was also tested (Appendix I). The results of the test showed a non-significant interaction between *Reliability Level* (IV) and *Employer* (covariate) in the one-way and two-way data, indicating that this assumption was not violated.

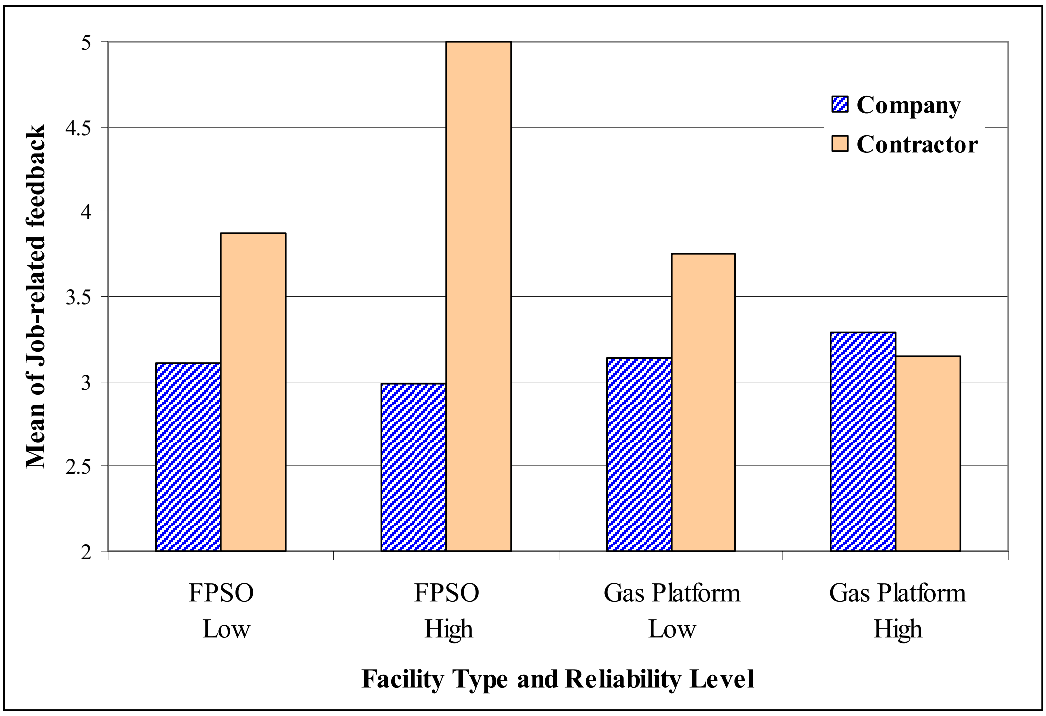

Figure 15. Mean differences between company and contractor on *Job-related feedback.*

A two-way ANCOVA was conducted to compare the effect of *Reliability Level* and *Facility Type* on *Job-related feedback* scores. *Employer* was included as the covariate to control for differences between company employees and contractors. The ANCOVA indicated that *Reliability Level* was not found to have a significant main effect on respondent's perceptions of *Job-related feedback,* $F(1, 78)=.106$, $p=.746$, partial $\eta^2=.001$. No significant interaction was observed between *Reliability Level* and *Facility Type*, $F(1, 78)=.002$, $p=.965$, partial $\eta^2=.000$.

A one-way ANCOVA was conducted to compare the effect of *Reliability Level* on *Job-related feedback* scores in FPSOs. *Employer* was included as the covariate to control for differences between company employees and contractors. The ANCOVA indicated that *Reliability Level* was not found to have a significant effect on *Job-related feedback,* $F(2,46)=.626$, $p=.539$, partial $\eta^2=.026$.

7.3.4.5 Information about change

A two-way Between-groups ANOVA was conducted to compare the responses to the *Information about change* scale at two reliability levels and for two facility types.

To determine the suitability of the data for analysis of variance, a Shapiro-Wilk Test for normality and Levene's Test for the homogeneity of variance were conducted (Appendix I). The assumption of normality was not violated, but the assumption of homogeneity was violated for the two-way data. Allen and Bennett (Allen & Bennett, 2008) do not consider this a concern when groups are equal in size and are moderately large.

The results of the two-way ANOVA showed no significant main effect of *Reliability Level* on perceptions of *Information about change, F* (1,82) = .860, *p*=.356, partial η^2 = .010. No interaction effect between *Reliability Level* and *Facility Type* was observed, *F* (1,82) = .026, *p*=.873, partial η^2 = .000.

A one-way Between-groups ANOVA was used to compare the responses to the items in the *Information about change* scale across FPSOs at three reliability levels. The result of the ANOVA indicated that there was no significant main effect of *Reliability Level* on perceptions of *Information about change*, *F* (2,50) = .249, *p*=.780, partial η^2 = .010.

7.4 Discussion

Study 3 was designed to test the hypotheses that there are significant differences in the perceptions of *Problem-solving, Vigilance, Design & Maintenance*, and *Organisational Communication* between lower, middle, and higher reliability work areas, across all facility types. The results of the Study 3 survey demonstrated that significant group differences between work areas existed in the responses to *Problem-solving* and *Design & Maintenance* items, but not the other variables. H_3 was supported, and H_1 was partially supported, but the direction was reversed from that which was expected. H_2 and H_4 were not supported.

7.4.1 Validity of the dependent variables

Reliability testing confirmed acceptable (α>.72) internal reliability levels (Table 15) for all variables except *Problem-solving* (α=.675). An Exploratory Factor Analysis of *Design & Maintenance* items found that the highest internal reliability (α=.729) was obtained when all items from the original scale were included in a single variable. This supported the contention that a single construct was being measured. A Factor Analysis of the communication items from the OCD/2 indicated that most of these items loaded onto two factors, which were named *Job-related feedback* (JRF) and *Information about change* (IAC) based on commonalities between the items in each scale. JRF concerned individual-level information specific to the person's own work, originating from supervisor's and staff meetings, as well as a general level of satisfaction with information availability. *Information about change* concerned information about workgroup and organisational level changes, as well as training. The items in these two variables were similar to those in the OCD/2 scales, providing confidence in the consistency of the original scales.

Overall, the variances accounted for in the factor structure were low, particularly for the communication variables, *Job-related feedback* (15.3%) and *Information about change* (14.5%). This was partly due to a complicated factor structure, consisting of a number of cross-loadings. Further research is needed to design an instrument for organisational communication which measures the quality of communication and information flow that is specific to heavy industry and off-shore environments, as distinct from office and factory environments. Some understanding of these different requirements was obtained from the comments of respondents discussed in the next chapter.

7.4.2 Problem-solving

Based on the recurrence of assumptions identified in Study 2 failures, *Problem-solving* was a construct that was expected to differentiate groups based on relative reliability. The four items used to measure *Problem-solving* were taken from the Work Design Questionnaire (Morgeson & Humphrey, 2006). The intent was to measure the underlying contributors to assumptions made in the course of finding solutions to equipment requiring repairs. The items in this scale measure perceptions of the tasks that are typically confronted in maintenance work; namely, task situations that are likely to lead to reliance on assumptions rather than accurate information. For example, questions enquire whether the person's job involves problems not encountered before, problems with no obvious correct answer, or problems requiring unique ideas or solutions. Additionally there is an item asking whether the job requires creativity. Agreement does not automatically imply that assumptions will be made, but that tasks may entail additional problem-solving behaviours and skills on the part of the respondent.

A significant relationship between *Problem-solving* and reliability level was observed in both the one-way and two-way (Figure 13) ANOVAs. In the one-way ANOVA, a large effect (14% of variance) was attributable to *Problem-solving*, with a Post-hoc analysis indicating that the difference between the lowest and middle reliability work areas was significant. In both the one-way (FPSOs) and two-way analyses (FPSOs and gas platforms), the slopes were negative, demonstrating that lower reliability was associated with agreement with statements about dealing with problems not encountered before or having no obvious answer, and the need for unique ideas and creativity. Based on human factors literature (Section 2.9.5), it was expected that personnel in higher reliability work areas would be more cognisant of acquiring and utilising problem-solving skills; that is, awareness of problem-solving requirements would be predictive of better outcomes from maintenance activities.

The significant results from the ANOVAs for the FPSOs partially supported Hypothesis H_1, that is, that there are differences in perceptions of *Problem-solving* between work areas, based on reliability level. However, the *Problem-solving* measure was found to be negatively related to reliability performance as experienced by maintenance personnel. This finding demonstrated that there is, in fact, a greater perceived requirement for problem-solving skills in a lower reliability work area. With increased reliability, the experience of no obvious solutions to problems, a need for unique solutions, and dealing with problems not encountered previously was observed to decrease. While it is difficult to assign causality from the results of the ANOVA, it might be inferred from the analysis results that lower work area reliability is predictive of a requirement for more frequent problem-solving behaviours. This contention is supported by the significant negative correlation of *Problem-solving* with *Design & Maintenance* (Table 15). An association between the need for problem-solving skills and an awareness of the inadequacies of technical designs and maintainability is logical. These findings might indicate a moderating role for problem-solving skills in the relationship between reliability, and design and maintainability. If this is the case, the *Problem-solving* variable might provide a measure of the importance of this moderating function. Further research would be required to test for such a moderating role.

7.4.3 Vigilance

The *Vigilance* scale from the Melbourne Decision-making Questionnaire (Mann, Burnett, Radford, & Ford, 1997) was also used to measure contributors to assumptions. It contained items such as "I like to consider all of the alternatives." The *Vigilance* scale was selected to test the characteristics of the workplace climate that promote methodicalness, or conversely could potentially provoke assumptions. Overall, the responses (Table 13) to the items in the *Vigilance* scale, were more positive (*M*=4.15) and uniform (*SD*=.38) than the other variables, indicating that most maintenance personnel generally consider themselves vigilant in the decision-making related to their tasks. This appeared to be relatively consistent across all work areas (Table 14), which may be the reason that no significant group differences based on reliability level were observed in the ANOVA. Hypothesis H_2 was therefore not supported. This may indicate that *Vigilance* is not a group-level dimension; rather that it is more characteristic of organisational-level climate in a company (Reiman, Oedewald & Rollenhagen, 2005), or individual-level personality trait (Mann et al, 1997), than an indicator of workgroup performance. Alternatively, the challenges of problem-solving may be more closely associated with reliability than vigilance in decision-making, as appears to be the case among service workgroups, such as nurses (Edmondson, 1996; Tucker, Edmondson, & Spear, 2002) and factory workers (MacDuffie, 1997). The relative importance of decision-making and problem-solving to maintenance personnel will be further explored in Chapter 8.

7.4.4 Design & Maintenance

The investigation questions for the *Design & Maintenance* code in HFIT were not designed as a survey scale and hence their use in this study required validating. However, the internal consistency (α=.729) of the loadings onto this variable support the contention that a single construct was being measured. Construct validity of the *Design & Maintenance* scale items was derived from the responses arising in the interviews in Study 2, which related to perceptions about the role of plant design and lack of maintenance in failures experienced. Plant design related to the maintainability of equipment, such as the adequacy of the structure, parts, and labelling, as well as the ease of installing parts, all of which would be expected to influence reliability (Wani & Gandhi, 1999).

In the one-way analysis of covariance of scores from FPSOs (Section 7.3.4.3), work areas could be significantly differentiated on the basis of *Design & Maintenance*. In this analysis, after controlling for the effect of *Time at Facility,* a large effect accounting for 21.5% of variance was observed with significant differences between the lowest and highest reliability work areas, and differences just outside the 95% confidence limit between the lowest and middle reliability work areas (Figure 14). These results indicated that the respondents from higher reliability work areas expressed greater agreement with items relating to the design and maintenance of their work areas, supporting Hypothesis H_3. In the two-way ANCOVA, a significant interaction effect was found between facility type and reliability level. Simple effects analyses indicated a significant relationship between reliability level and *Design & Maintenance* scores for the FPSOs, but not the gas platforms.

An association between plant design and reliability is well-accepted in engineering literature (Bea, 1998; Taylor, 2007). As well, the concept of maintainability based on objective measures of the ease of maintaining equipment has often been acknowledged in the engineering domain (Mason, 1990; Sharma & Kumar, 2008; Tjiparuro & Thompson, 2004; Wani & Gandhi, 1999). The results of this study demonstrated that a measure of the respondents' perceptions could distinguish between work areas on the basis of reliability level. In reviewing the literature, the issue of perceptions of plant maintainability and condition are given less prominence than engineering measures of maintenance productivity (Lofsten, 2000). In Lofsten's review, assessments of plant maintenance needs were almost universally based on productivity and cost considerations. However, the innate understanding of maintenance technicians of the condition of their workplace was borne out by the significant association between responses to the *Design & Maintenance* scale and reliability level in data from both the one-way and two-way analyses. As Cooke (2002) contends, maintenance technicians working with, and in physical proximity to, equipment "may be able to contribute far more to the success of the business than they are currently doing" (p. 968). This would certainly be the case if, as the analysis indicates, maintenance technicians can assess the state of their plant and its requirements with a degree of accuracy.

The importance of experience in comprehending plant maintenance condition was further supported by the significant effect of *Time at Facility* on scores for *Design & Maintenance*. Understanding of the correct operation of processes in the workplace would be expected to develop over time and with experience, though this is not often recognised by organisations (Cooke, 2002). Time in one's facility would influence perceptions of most human factors relating to a person's workplace, but particularly issues of maintainability for maintenance personal whose principal task is to ensure that equipment operates as required. Recognising the deficiencies in the maintainability of equipment is a factor that would be more apparent as workplace knowledge increases over time (Pettersen & Aase, 2007), as demonstrated by the negative relationship found between *Design & Maintenance* and *Time at Facility* (Table 15). Responses to this variable therefore appeared to be sensitive to an increased awareness among participants developed through their experience over time. The average age of the workforce was relatively high (*M*= 42.3 years) and so this effect may not be as apparent in a younger, less-experienced workforce.

In addition to *Time at Facility*, as discussed above, significant correlations were observed (Table 15) between responses to the *Design & Maintenance* items and several other variables. The correlation with *Problem-solving* was negative, indicating that negative perceptions of plant design and maintainability were associated with a greater requirement for problem-solving, such as when facing new problems and problems with no obvious answer. Correlations with *Vigilance, Job-related feedback,* and *Information about change* were significant, demonstrating the influence of workplace design on various dimensions of the maintenance workplace, such as *Methodicalness* described by Oedewald and Reiman (2002) and O*rganisational Communication* (Bourrier, 2005).

7.4.5 Organisational communication

Job-related feedback and *Information about change* contained items extracted through a Factor Analysis of the scales in the OCD/2 instrument (Wiio, 1978a). The four items that loaded onto *Job-related feedback* concerned the respondents' perception of the overall level of communication in the organisation, as well as specific job-related information from supervisors and staff meetings. The four items that loaded onto *Information about change* concerned the respondent's perception of the amount of communication received relating to changes in production, procedures, and the organisation itself. An additional item, relating to information about training also loaded onto this factor. There was a strong relationship between *Job-related feedback* and *Information about change* as shown by the significant correlation between them (Table 15). A significant positive correlation was also noted between the two communication variables and *Design & Maintenance*. In the case of *Job-related feedback*, these attitudes were also found to be significantly correlated with *Employer* (company employee vs. contractor). *Information about change* had the lowest mean for any variable (Table 13) and the second highest standard deviation of the variables, indicating a lower satisfaction with organisational information, accompanied by a broader range of views.

The ANCOVA conducted on *Job-related feedback* and the ANOVA conducted on *Information about change* did not indicate significant group differences between high and low reliability work areas. Therefore, Hypothesis H_4 was not supported. From these results, despite the prominent role played by *Communication* as a contributor to Study 2 failures, it did not appear that organisational communication was directly related to reliability level as tested in Study 3. The implication is that communication between individuals has a role in the avoidance of failures, but not a direct influence on reliability in terms of day-to-day activities. The reason for the absence of an observed effect may lie in the nature of organisational communication. A lack of communication in the workplace can be expected to increase the potential for a system failure, and consequently teams in HROs were observed to rely on nearly-continuous communication (Rochlin, 1999). However, from the findings of Study 3, the routine performance of maintenance tasks appeared to be hindered less by poor communication than by other factors, such as plant design and problem-solving requirements. Effective communication is known to reduce the level of uncertainty between team members (Sasou & Reason, 1999) and improve team efficiencies (Zohar & Luria, 2003a), but might not have a significant impact on overall group effectiveness. From this point of view, poor communication is likely to increase the difficulty of tasks, but might not greatly influence outcomes, other than as a co-contributor to a multi-factor failure.

An alternative explanation for the absence of a significant effect on reliability may be that the direct effect of communication on maintenance processes may not be detectable with the measures used. In a study of military communication (O'Reilly & Roberts, 1977), communication variables (i.e. accuracy and openness) were not found to have a straightforward effect on organisational performance, but rather were part of a process that mediated between group structures and organisational effectiveness. In that study, existing group structures were found to have a significant effect on communication measures, and in turn it was considered that performance affected communication. Other factors may have an important influence on communication, as demonstrated by the significant correlations between *Job-related feedback* and *Design & Maintenance*, *Vigilance,* and *Employer*, and so might mask a direct relationship between communication and reliability. As such, it may be difficult to measure directly the influence of communication on plant maintenance performance without controlling for a range of latent and demographic factors. For example, a significant relationship was found between perceptions of *Job-related Feedback* and *Employer* as a covariate with *Reliability Level* (Figure 15), indicating that this influence on organisational communication can vary from company to company. In the next chapter, the analysis of the comments section of the survey may assist in resolving the issues concerning the role of communication in the effectiveness of maintenance activities.

7.4.6 Limitations of the study

The lack of significant results supporting H_2 and H_4 may have been due to the absence of group level effects, as described above, or due to the presence of confounding effects that mask direct relationships between reliability level and the dependant variables. Other reasons for the absence of significant relationships between reliability level and the dependant variables are also considered below, including the properties of the measures and the samples used in Study 3.

7.4.6.1 Measures

The measures used were selected to test the factors identified in Study 2. Where possible, they were selected from those available in the literature that were validated and tested for internal consistency. The measures for *Problem-solving* and *Vigilance* had undergone extensive testing (Mann, Burnett, Radford, & Ford, 1997; Morgeson & Humphrey, 2006). *Problem-solving* showed a significant relationship to reliability level, but *Vigilance* scores did not differentiate lower and higher reliability work areas. The wording of items in the *Vigilance* scale could be improved to be more sensitive to group differences. For example, the items in the scale produced a uniformly positive response (*M*=4.15, *SD* =.382), offering little basis for between-group differentiation. An approach that might generate a greater diversity of responses would require re-phrasing the items from individual-level statements to workgroup-level statements. As an example, Item 18 would become, "*Members of my workgroup* take a lot of care before choosing how to do a job (Agree/Disagree)." In addition to realigning these items with the workgroup level, respondents may be better able to assess their team's shared mental models more accurately than their own behaviour (Mathieu, Goodwin, Heffner, Salas, & Cannon-Bowers, 2000). Re-phrasing the wording of items to match the descriptions of assumptions in Study 2 may also improve the sensitivity of the measure.

Confounding effects may also have been a factor in the lack of significant results for *Vigilance*. *Vigilance*, which is similar to *Methodicalness* in the Maintenance Core Task model (Oedewald & Reiman, 2002), is one of several dimensions that contribute to the quality of decision-making in maintenance activities. It is possible that *Vigilance* is moderated by these other dimensions of the maintenance task, and that the selected measure was therefore not sensitive enough to differentiate between groups without controlling for these complex interactions in decision-making.

Construct validity was a concern with the *Design & Maintenance* scale. No validated instrument for perceptions of plant maintainability and maintenance condition could be identified in the literature. The questions in HFIT were intended for incident investigation and so validation would need to be done to increase confidence that the constructs of plant maintainability and maintenance condition were being measured. The relatively high loadings for individual items and the internal reliability (α=.729) obtained from Factor Analysis indicated the potential to use this scale as a measure of maintainability, and so further testing of construct validity is warranted.

Finally, uncertainty about the factor structure of the *Organisational Communication* scales required a factor analysis to confirm the constructs in the original scales (Wiio, 1978b). *Job-related feedback* and *Information about change* appeared to be unable to significantly discriminate work areas based on reliability level, despite communication being a frequent contributor to maintenance failures. In addition, the overall variance explained by these factors was relatively low (15% each for *Job-related feedback* and *Information about change*). *Information about change* mainly reflects organisation-wide information exchange, and may therefore not be sufficiently sensitive to group-level differences, upon which Study 3 was based. *Job-related feedback* could be considered a group-level process, as it focuses on perceptions about interactions with others in the immediate work environment (i.e. supervisors and other team members), but may also be sensitive to organisation-level phenomena, as the relationship to *Employer* demonstrated. Again, better scale selection and refinement of questionnaire items may be required in order to ensure that the nature of group-level communication, as experienced in specific work areas, is being measured. Specific themes relating to group- and organisation-level communication will be examined through the comments provided by the respondents.

7.4.6.2 Sample size

Although the overall number of valid responses (n=172) was sufficient for Factor Analysis and ANOVAs, 39 responses were eliminated from the ANOVAs because the respondents indicated that they worked across all areas of the Process Plant, and five respondents marked both Gas Platform 1 and Gas Platform 2 as their work areas. This was unexpected as maintenance personnel are generally affiliated with a particular facility or Process Plant work area. However, a relatively high percentage of respondents were contractors (34%) and they tend to be assigned to different work areas as required. Nearly all (95%) of the respondents who noted that they worked in all areas of the Process Plant were contractors. In addition, the differences in response rate between facilities (Table 12) and the low number of responses from smaller facilities, such as Gas Platform 3 and FPSO 1, compromised several of the planned comparisons. Notably, the original 3x3 design was reconfigured to 2x2 and 1x3 designs, to accommodate the data obtained. These sampling flaws could have been rectified by requesting that respondents only nominate their most frequent workplace and by greater canvassing of smaller facilities, respectively. However, these interventions could also introduce other biases into the data.

Alternatively, the effect size may have been too small to detect a significant effect for the size of sample available from the population of maintenance personnel. In much of the data, the differences in means were as predicted by the hypotheses, but were not found to be statistically significant. For example, in Figure 14, the relationship Lowest-to-Highest reliability is significant, and Lowest-to-Middle reliability is close to significant, but not Middle-to-Highest reliability. A larger sample size, obtainable through a higher response rate, would provide more statistical power, though the effect size may still be too small to be of practical significance. Finally, the differences in reliability level between groups (the Independent Variable) may not have been sufficiently large to produce significant differences between the factors being analysed (the Dependent Variables). A comparison with reliability levels in other organisations may indicate the relative magnitude of the differences between the groups in Study 3.

7.5 Summary and Conclusions

The results of Study 3 partially supported hypotheses H_1 and H_3, namely that significant group differences in perceptions existed in the variables *Problem-solving* and *Design & Maintenance* based on reliability level, but not for all facility types. Higher reliability was associated with perceptions of better maintainability and plant designs. Lower reliability was associated with a greater perceived requirement for problem-solving behaviours, as defined by the survey items. Hypotheses H_2 and H_4 were not supported; it was found that perceptions of *Vigilance* and *Organisational Communication*, as measured in this study, were not sensitive to the differences in reliability level of work areas. One implication was that behaviours involving vigilance and communication within the organisation were significant factors in failures related to maintenance activities, but not significant factors in day-to-day reliability. An alternative explanation was that the particular measures selected for testing *Vigilance* and *Organisational Communication* were not sensitive to group-level differences, either due to individual- and organisation-level phenomena that moderate the relationship of these factors to reliability, or due to confounding interactions between variables. The comments made by respondents reviewed in the next chapter may assist in resolving which alternative is more likely.

8.0 Examining Human Factors in Comments from the Study 3 Survey

8.1 Introduction

8.1.1 Objective and rationale for the analysis of survey comments

The quantitative survey results reported in Chapter 7 showed significant group differences in *Design & Maintenance* and *Problem-solving*, related to work area reliability level. *Job-related Feedback* showed significant group differences related to *Employer.* No significant statistical differences were observed in the other two variables, *Vigilance* and *Information about change*. This chapter provides an examination of the open-ended comments made at the end of the survey described in Chapter 7. The objective of the analysis of the comments section was to use qualitative data to triangulate the quantitative data from the survey in Study 3, in order to aid in the interpretation of the inferential analyses discussed in Section 7.4. The comments section of the survey was also intended to accord maintenance personnel an opportunity to express their opinions concerning the factors that they believe to impact on their tasks and workplace. In this way, the comments section was intended to clarify the interpretation of the quantitative data.

Todd, Nerlich, McKeown, and Clarke (2004) described between-methods triangulation as the use of a second method to obtain data in order to confirm or refute the findings from a previously used method. For example, in their assessment of the cultural dimensions of maintenance reliability in NPPs, Reiman and Oedewald (2006a) used semi-structured interviews and group sessions to support the results of their CULTURE questionnaire. Robert, Rousseau, and La Porte (1994) used focus groups and reviews with officers to triangulate the results from a cultural assessment questionnaire in their study of aircraft carriers as HROs. In another example, Todd and Lobeck (2004) described the combination of questionnaire and group interview methods to clarify and explain issues arising from their survey of the attitudes of English and German language learners towards the respective countries and people. Resolving apparent contradictions between their survey and interview results led to a refinement of the explanation of their survey results and reconsideration of the importance of personal experience in explaining attitudes. Similarly, applying an alternative method of obtaining data from respondents in Study 3 provided a means of testing the results obtained from the quantitative analysis of the questionnaire data, and resolving any ambiguity in the analysis of the data.

Ambiguities did arise in interpreting the data relating to several variables in Study 3 (see Section 7.4 and 7.5). For example, questions remained from the quantitative analysis in Study 3 as to why, despite the frequency of communication problems contributing to failures reported in Study 2, the two communication variables *Job-related Feedback* and *Information about change* were not associated with significant group differences in reliability level. The comment section thus provided an opportunity to resolve some of these anomalies and improve the theoretical understanding derived from the survey.

To clarify the meaning of anomalies may require, as Todd et al (2004) argued, an understanding of the subjective realities of the people *researched*, which they termed 'repopulating psychology.' For example, the analysis of comments was intended to determine whether the five survey variables derived from responses are related to dimensions of the workplace recognised by maintenance personnel. Although the methodology of Study 2 narrowed the range of human factors that would be tested in Study 3 to the three most-frequent contributors to past failures, these factors may not necessarily be the ones of greatest concern to maintenance personnel. The use of an open-ended question in the survey, concerning hindrances and aids to maintenance work, was intended to determine if factors other than the three most-frequent factors in failures were considered by maintenance personnel as affecting their work.

Finally, another aspect of mixing methods that Todd et al. (2004) advocated was improving the mutual understanding between practitioners in psychology and the people that are 'consumers' of this knowledge. The expected users of the knowledge gained from Study 3, namely maintenance supervisors and managers, will be better able to understand its implications by referring to the explanatory material in the comments. Making this connection between the theoretical implications of data and a practical understanding of it was described by Reason and Hobbs (2003) as 'theory in use.' The ability of maintenance personnel to explain workplace phenomena derives from their understanding of the local workplace, particularly the informal structures and relationships. Dekker (2006) called this understanding, the Local Rationality Principle. He argued that workers would interpret their role in an organisation based on "their knowledge of the situation, their objectives, and the objectives of the larger organisation they work for" (p.13). Based on this interpretive ability, it was intended that the comments section of the survey would clarify the perceptions of maintenance personnel as 'voiced' in the survey, and accord them an opportunity to express 'in their own words' their opinions concerning the factors that impacted on their tasks and workplace.

Lyons and Coyle (2007) described several approaches for obtaining and analysing the opinions of people 'in their own words' in qualitative data. Storey (2007) explained one method that has been developed to interpret themes within a body of text data, named Interpretive Phenomenological Analysis (IPA). An IPA approach was adopted in this study in order to extract themes from the text provided by respondents. IPA, as the name implies, is a form of content analysis that deals with empirical phenomena requiring interpretation to extract meaning and understanding. Smith (2004) described IPA as a phenomenological approach to exploring the experience of an individual in a context, such as a maintenance technician in a petroleum industry workplace. In addition, he explains that there are two levels of interpretation involved in IPA, namely 1) the sense that the participant makes of his or her world, and 2) the understanding that the researcher is trying to obtain from the participant's words. In Study 3, by asking what hinders and helps maintenance, the participant was being asked about the factors he or she believed influences the performance of maintenance and ultimately reliability, which was also the objective of the 30 questionnaire items in the survey. However, in regard to the comments, it was more the personal experience of organisational factors, in the participant's own words, which was being analysed, rather than a multiple-choice response to specific questions chosen for the survey. In this chapter, the findings of a content analysis of these comments are presented, along with an examination of their relationship to the other data collected in the current research.

8.2 Method

8.2.1 Participants

Participants surveyed in Study 3 included maintenance technicians, maintenance supervisors and maintenance coordinator/planners as described in Section 7.2.2. Of the 178 participants who returned a completed questionnaire, 101 (55.6%) included a written comment. Among these participants, 58.5% of company personnel offered comments, while 56.9% of contractors commented. Regarding facility type, comments were received from gas platforms (63.4%), FPSOs (47.2%) and the Process Plant (59.7%).

8.2.2 Measure

The source of data for the qualitative analysis was the fourth and final section of the survey (Appendix F) sent to maintenance personnel across the target company. The procedure for supplying survey forms was described in Section 7.2.4. This section of the survey was an open-ended request for the participant to, "Please write any comments you have on what helps or gets in the way of maintenance work at [the company]." Five blank lines were then provided for the insertion of a response.

8.2.3 Data processing

The comments supplied were entered verbatim into a Microsoft Excel spreadsheet with the ID code of the respondent. Analysis of the comments commenced with a careful reading and re-reading of the text provided by respondents in order to analyse their thematic content. Next, a listing of sub-themes was extracted from the individual comments. The framework adopted for themes and sub-themes was consistent with the HFIT taxonomy of human factors in operational failures, but derived from the respondent's own words. Based on this framework, sub-themes were extracted from the comments. Constructs common to these sub-themes were then the basis for grouping sub-themes into a smaller number of shared themes.

The conceptual and empirical implications of the themes were then considered to determine if a still smaller set of over-arching themes, termed 'super-ordinate themes' in IPA, could be discerned. After assigning sub-themes, themes and super-ordinate themes, the comments were then re-assessed to determine if sub-theme and super-ordinate theme categories were appropriate. The frequencies of themes and super-ordinate themes were then determined and associations with demographic variables were investigated.

8.3 Results

8.3.1 Demographic data

The respondents' comments ranged from short statements of a single word (e.g. "Politics" and "SAP") through to longer assessments (i.e., a maximum of 131 words) of multiple factors that impact on their workplace. The majority of comments (79.8%) identified hindrances, rather than aids, to conducting maintenance work. The number of responses with comments and no comments made, arranged by facility and reliability level, is shown in Figure 16. The proportion of respondents making comments did not appear to be related to reliability level. For example, even in several higher reliability facilities (e.g. Gas Platform 1 and Process Plant 1) there were more participants making comments than not, with proportions similar to middle reliability facilities, such as Gas Platform 2 and FPSO 2.

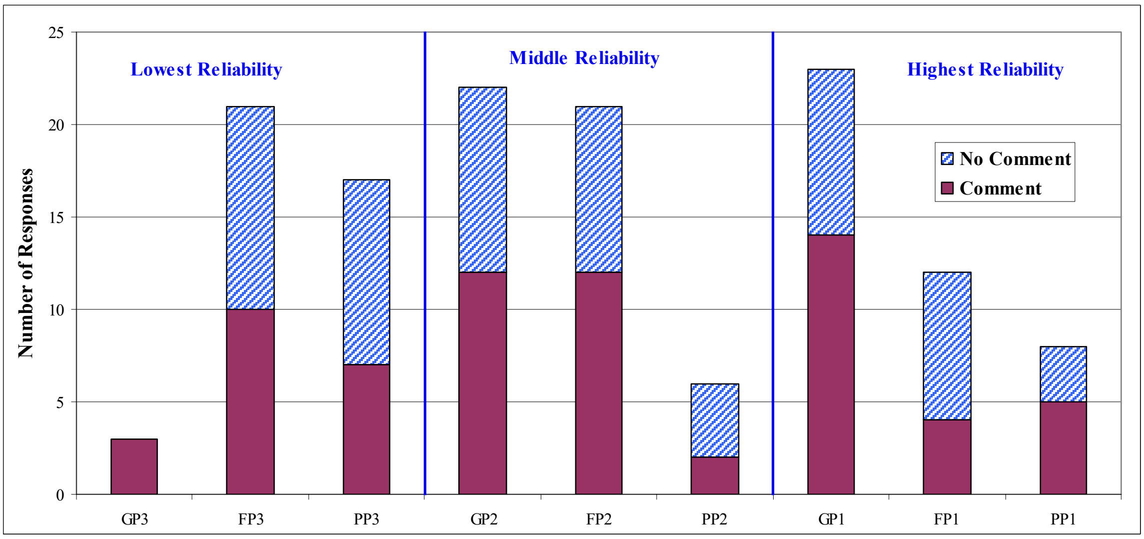

Figure 16. Frequency of comments and no comments supplied, arranged by facility and reliability level.

8.3.2 Sub-themes, themes and overarching themes

Content Analysis of the 101 comments resulted in the extraction of 57 sub-themes. The 57 sub-themes were grouped into 12 themes by conceptually linking the ideas expressed by the participants. Table 16 shows the 12 themes and the sub-themes related to each theme, and the number of participants who made a comment concerning each theme. Examples of comments for each of the 12 themes are provided in Table 17.

Table 16. Twelve themes derived from 57 sub-themes extracted from the survey respondents' comments, and the number of respondents mentioning each theme.

Themes	Sub-Themes	Freq.
Communication processes	Lack of communication between departments Information from supervisor not consistent. Little contact with production	8
Planning and work scopes	Planning scopes of work Poor planning.	11
Workloads and time pressures	Many jobs on the go. High work load. No job levelling. Not enough time.	7
Poor decision-making	Decision-making too fast, inconsistent; no understanding of issues. Operations not allowing work to be completed Repeating maintenance errors-not documenting lessons learned Not prepared to shutdown equipment for maintenance . 'Breakdown' approach Inflexibility in changing Operations model	16
Better work systems-workplace efficiency	Need for proactivity; not doing things smarter Long lead times. Maintainers bogged down with SAP, computer work QA needs improvement; KEQ causes unnecessary hold-ups. Confusing permit system; hard to implement Permit system delays work Changes not fully rolled out Lack of transport to job-site. Too many private vehicles. Too much administration/paperwork Management of change takes too long. Limited resources for new systems. Delays to work that reduce efficiency	57
Shortage of personnel & Support staff/Teamwork	On-board planner/activity coordinator needed Need to be team players/assist one another. Insufficient personnel; more people needed Slow engineering dept. On-board engineer needed	24
Training needs & Competency	Training opportunities inadequate. Competency, e.g. in plant operations; more reliance on experienced staff.	13
Procedures & work direction	Few procedures Procedures not up-to-date or incorrect Procedures take too long to implement	10

Themes	Sub-Themes	Freq.
Lack of information	Information hard to find, e.g. how the plant works Lack of drawings and technical data Job-related knowledge is word-of-mouth from workmates Difficult to locate information in SAP. SAP needs improvement Poor BOMs. BOMs behind the times, e.g., need pictures Information sessions to know the big picture Out of date information, e.g. maintenance orders, telephone lists SAP not set-up or used correctly; differences across facilities	28
Management & supervision	Operators control maintainers work Lack of management participation at meetings Team leader supervision is good Not enough supervision Top heavy in staff who make excuses; seat polishers Focus on costs without understanding contributors to costs. Politics Lack of cohesion/cooperation between depts (e.g. MM & CC) H&S culture poor. Production before safety	21
Workforce consistency	Consistency of personnel, e.g. between shifts High staff turnover Changes not fully rolled out Too many contractors & different companies.	7
Equipment & spares	Problems with ageing plant and machines Inadequate spares Lack of tools or equipment, e.g. two-way radios Problems with quality of vendor parts and repairs Involve maintainers in design. Standardise equipment designs.	15

Table 17. Themes and examples derived from comments written by participants. (Participant identification number in parentheses)

Code	Theme	Example
A	Communication processes	"It seems to me that there is a distinct lack of communication between the offshore facility, [company headquarters] and outside contractors/vendors."(#111). **Sub-theme:** Delays to work (e.g. permit system). Desire for better efficiency "There are a lot of delays when a problem is crossed on a job before getting an answer" (#106). **Sub-theme:** Need for good planning (e.g. proactive approach) "Lack of communication between –[the company] & contractors -Management & workers (contractors)" (#44). **Sub-theme:** Delays to work (e.g. permit system). Desire for better efficiency.
B	Planning and work scopes	"Activity Coordinator/Planner was a Godsend for day to day activities-maybe the role will come back one day to assist all work groups" (#10). **Sub-theme:** Planning scopes of work "We are average at best when planning for major maintenance. The great technical integrity results on NE are more a result of excellent personnel than good organization & planning" (#125). **Sub-theme:** Poor planning.
C	Workloads and time pressures	"Increasingly there is insufficient time for necessary planned work as breakdown maintenance consumes a considerable amount of my time. Job satisfaction has diminished, as there is not enough time at the end of corrective work to document Lessons Learned and make some notes for 'similar' faults" (#149). **Sub-themes:** Not enough time, Repeating maintenance errors-not documenting lessons learned. "Team leaders [are] massively overworked with their managers focusing on bullshit items" (#118). **Sub-theme:** Many jobs on the go. High work load. No job levelling.

D	Poor decision-making	"Our decision making process is always too fast, I don't have enough time to think about decisions. One day we will make the wrong move due to poor planning" (#8). **Sub-theme:** Decision-making too fast, inconsistent; no understanding of issues. "Continually repeating maintenance errors. Not prepared to shut down equipment until it breaks down. Maintenance staff making decisions on equipment they have no knowledge or understanding of its function" (#119). **Sub-themes**: Repeating maintenance errors-not documenting lessons learned, Not prepared to shut down equipment for maintenance. *Breakdown* approach.
E	Better work systems-workplace efficiency	"Getting changes/modifications through the system is very time consuming" (#108). **Sub-theme:** Management of change takes too long. Limited resources for new systems. "At present -permit to work & operation planning is inefficient" (#80). **Sub-theme:** Permit system delays work. "Having a planner on board the facility would be a more efficient way of resourcing work orders and parts in general" (#107). **Sub-theme:** Delays to work that reduce efficiency
F	Shortage of personnel & Support staff/Teamwork	"At the moment onboard the [FP3] the main thing that gets in the way of maintenance is the lack of personnel. For the last few months there has been one fitter onboard as core crew to carry out maintenance" (#49). **Sub-theme:** Insufficient personnel; more people needed. "Waiting for equipment to get to your work area, as we only have one (electrical?) to look after work areas, e.g. 4-5 work areas may be open up anywhere on site" (#103). **Sub-theme:** Insufficient personnel; more people needed.

G	Training needs & Competency	"Previous/ original employees of [the company] were given frequent training of equipment, ensuring competency. This has been reduced significantly leaving reliance on older staff" (#11). **Sub-theme:** Competency, e.g. in plant operations; more reliance on experienced staff. "Training opportunities have been restricted compared to early years. Double standard" (#9). **Sub-theme:** Training opportunities inadequate. "Training for both new starters and existing employees is also inadequate and can compromise plant integrity" (#166). **Sub-theme:** Training opportunities inadequate.
H	Procedures & work direction	"The main problem retarding my way forward is two-fold, 1.lack of up-to-date procedures, 2…"(#22). **Sub-theme:** Procedures not up-to-date or incorrect. "A good percentage of procedures are out of date/wrong and require updates. Changes are slow & require validating" (#116). **Sub-theme**: Management of change takes too long. Limited resources for new systems. "Existing and new procedures are inadequate and compromise safety" (#166). **Sub-theme:** Few procedures.
I	Lack of information	"95% of the site/plant/job knowledge is word of mouth from workmates experience on site. I find the bulk of info is on the intranet, SAP, etc, however, I often give up as I cannot locate it in search fields, etc." (#29). **Sub-theme:** Job-related knowledge is word-of-mouth from workmates. "A fair bit of skill is involved in getting/ finding information on a certain piece of equipment (e.g. searching in CDD, library etc). Could be made easier" (#131). **Sub-theme:** Information hard to find, e.g. how the plant works. "Information transfer from supervisors, SAP group to maintenance personnel need to be improved" (#142). **Sub-theme:** SAP not set-up or used correctly; differences across facilities.

J	Management & supervision	“Very little to no supervision“(#29). **Sub-theme**: Not enough supervision. “Far too much admin. As a supervisor my day is spent accounting to bean counters and tracking paperwork rather than spending time on the job” (#38). **Sub-theme:** Too much administration/paperwork. “Management focus on maintenance costs without any understanding of what contributes to these costs. Many audits have been initiated whose only objective measure of success is to save money” (#70). **Sub-theme:** Focus on costs without understanding contributors to costs. “Helps: Good supervision from our direct team leader [name deleted] and our resource estimators” (#17). **Sub-theme:** Team leader supervision is good.
K	Workforce consistency	“Operations have no consistency from shift to shift” (#23). **Sub-theme:** Consistency of personnel, e.g. between shifts. “The permit system is very inconsistent. Inconsistency between Operations shifts in decision making” (#42). **Sub-theme:** Consistency of personnel, e.g. between shifts.
L	Equipment & spares	“Materials /parts availability is a big issue on planned work. Many jobs cannot be completed in time due to lack of materials” (#150). **Sub-theme:** Inadequate spares. “Procurement times for parts/long lead times [is a] ‘very big issue’” (#9). **Sub-theme:** Inadequate spares. “Stock level of parts [is] very poor, and takes too long to order and receive equipment” (#34). Sub-theme: Inadequate spares.

Based on conceptual linkages between these 12 themes, four super-ordinate themes were identified:

- Communication and access to information
- Efficiency of current work systems
- Need for more personnel and better workgroup support systems
- Management & supervisory impacts on the workplace.

The relationship between themes and super-ordinate themes and the frequencies of the super-ordinate themes are shown in Table 18. The super-ordinate theme *Communication and access to information* refers to comments made concerning faulty communication processes, specific needs for procedures and work direction, or the difficulty of obtaining information. For example, a mechanical maintenance technician on an FPSO commented, "A fair bit of skill is involved in getting / finding information on a certain piece of equipment (e.g. searching in CDD, library etc). Could be made easier." (Response #131). A mechanical maintenance technician in the Process Plant commented, "Very few procedures; permit system can be frustrating & confusing. Little contact with production, i.e. how the plant works. Information is available but hard to find" (Response #13).

Table 18. Four super-ordinate themes derived from 12 themes listed in Tables 16 and 17.

Super-Ordinate Themes	Themes	Frequency
Communication and access to information	A,H,I	45
Efficiency of current work systems	B,E,L	85
Need for more personnel and better workgroup support systems	C,F,G,K	50
Management & supervisory impacts on the workplace	D,J	37

Efficiency of current work systems refers to the need for better work systems and workplace efficiency due to insufficient planning and work scopes, or problems encountered with equipment and spares. An Inlec on a gas platform blamed inefficiencies on "Material unavailability, hardly any spare parts on board, quality of returned items from vendor repairs is sometimes poor, [and] a lot of time wasted on SAP" (Response #66).

Need for more personnel and better workgroup support systems refers to perceptions of a mismatch between the tasks required and the personnel required to do these tasks. This can include a mismatch due to workloads and pressures, shortage of support personnel, lack of teamwork, insufficient training, or inconsistency in the workforce. A maintenance technician with more than 10 years experience on a gas platform commented that an "Activity coordinator/Planner was a godsend for day to day activities-maybe the role will come back one day to assist all work groups (Response #10).

Management & supervisory impacts on the workplace refers to poor-decision making or problems associated with supervision and management. A team leader from the Process Plant was concerned that, "Our decision-making process is always too fast, I don't have enough time to think about decisions. One day we will make the wrong move due to poor planning" (Response #8).

8.3.3 Super-ordinate themes and reliability

The frequency of the four super-ordinate themes and 12 themes was compared across facility type (Tables 19-21). Figure 17 represents the total distribution of super-ordinate themes in comments offered across the nine work areas, arranged by reliability level. The distribution of super-ordinate themes are indicated in the graph as percentages of the total number of comments made for the three facilities in each reliability level. It was apparent that the lowest reliability work areas provided a greater proportion of comments relating to *Management & supervisory impacts* on the workplace than did middle and highest reliability work areas. Similarly, one of the themes in *Management & supervisory impacts*, namely *Poor decision-making,* was more frequently mentioned in comments from lower reliability (13.2% of comments) compared to middle (5.2%) and higher (4.2%) reliability work areas. Conversely, the middle and highest reliability work areas provided a greater proportion of comments relating to *Efficiency of current work systems*. The proportions of comments relating to *Communication & access to information* and to a *Need for more personnel & better workgroup support systems* was similar across the three reliability levels.

Table 19. Frequency of comments expressed according to themes and super-ordinate themes for FPSOs, grouped by reliability level.

Super-Ordinate Themes	Theme	**Lower Reliability FPSO 3**		**Middle Reliability FPSO 2**		**Higher Reliability FPSO 1**	
		Super-Ordinate Theme	Theme	Super-Ordinate Theme	Theme	Super-Ordinate Theme	Theme
Communication and access to information	Communication processes	2	0	10	1	2	0
	Procedures & work direction		0		0		0
	Lack of information		2		9		2
Efficiency of current work systems	Planning and work scopes	4	1	5	1	2	1
	Better work systems-workplace efficiency		3		3		1
	Equipment & spares		0		1		0
Need for more personnel and better workgroup support systems	Workloads and time pressures	5	1	12	3	1	0
	Shortage of personnel & Support staff/Teamwork		2		6		0
	Training needs & Competency		2		2		1
	Workforce consistency		0		1		0
Management & supervisory impacts on the workplace	Poor decision-making	9	6	2	1	0	0
	Management & supervision		3		1		0

Table 20. Frequency of comments expressed according to themes and super-ordinate themes for gas platforms, grouped by reliability level.

Super-Ordinate Themes	Theme	Lower Reliability Gas Platform 3		Middle Reliability Gas Platform 2		Higher Reliability Gas Platform 1	
		Super-Ordinate Theme	Theme	Super-Ordinate Theme	Theme	Super-Ordinate Theme	Theme
Communication and access to information	Communication processes	2	0	2	0	6	2
	Procedures & work direction		0		0		1
	Lack of information		2		2		3
Efficiency of current work systems	Planning and work scopes	2	0	17	3	15	0
	Better work systems-workplace efficiency		1		12		13
	Equipment & spares		1		2		2
Need for more personnel and better workgroup support systems	Workloads and time pressures	1	0	2	0	9	0
	Shortage of personnel & Support staff/Teamwork		1		2		5
	Training needs & Competency		0		0		3
	Workforce consistency		0		0		1
Management & supervisory impacts on the workplace	Poor decision-making	1	0	2	2	2	0
	Management & supervision		1		0		2

Table 21. Frequency of comments according to themes and super-ordinate themes, and grouped by Process Plant work area reliability level.

Super-ordinate themes	Theme	**Lower Reliability Process Plant 3**		**Middle Reliability Process Plant 2**		**Higher Reliability Process Plant 1**	
		Super-Ordinate Theme	Theme	Super-Ordinate Theme	Theme	Super-Ordinate Theme	Theme
Communication and access to information	Communication processes	11	1	2	0	2	1
	Procedures & work direction		7		0		1
	Lack of information		3		2		0
Efficiency of current work systems	Planning and work scopes	4	1	1	0	3	1
	Better work systems-workplace efficiency		3		1		2
	Equipment & spares		0		0		0
Need for more personnel and better workgroup support systems	Workloads and time pressures	7	2	0	0	4	1
	Shortage of personnel & Support staff/Teamwork		0		0		1
	Training needs & Competency		3		0		1
	Workforce consistency		1		0		1
Management & supervisory impacts on the workplace	Poor decision-making	6	1	1	0	2	2
	Management & supervision		5		1		0

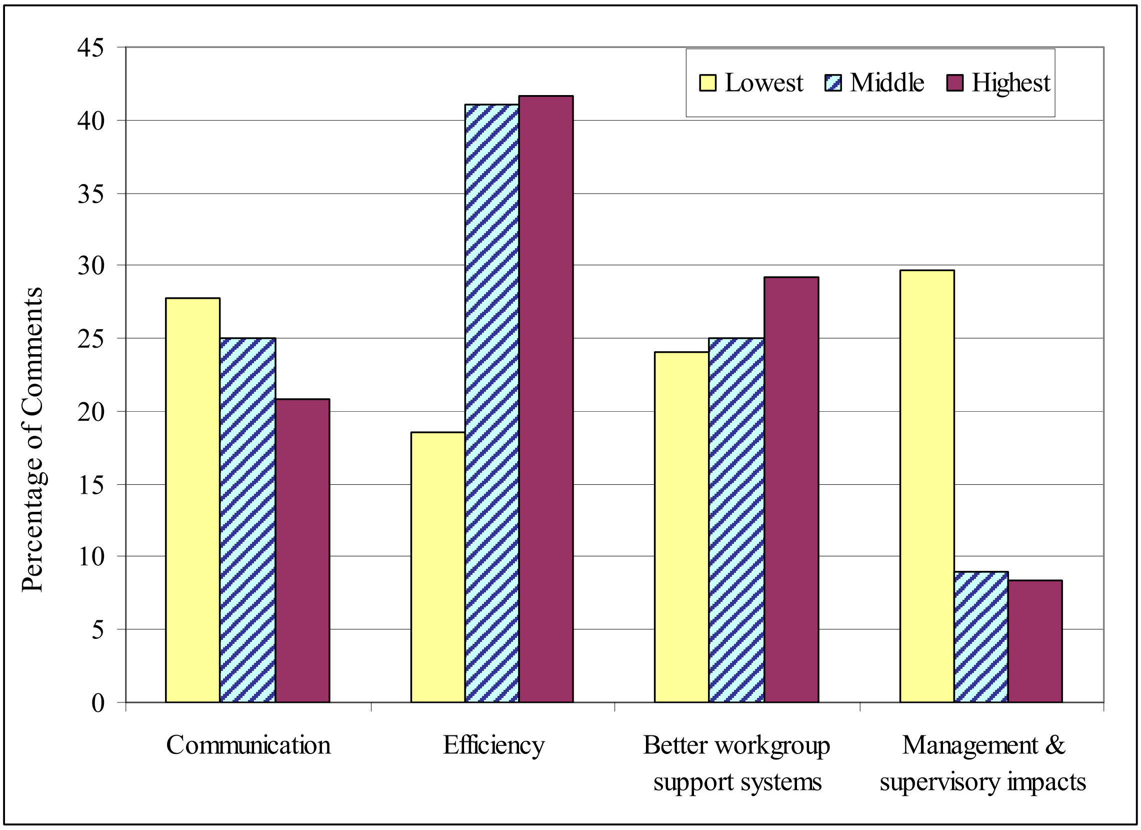

Figure 17. Distribution of super-ordinate themes in comments arranged by work area reliability level. Frequencies are given as percentages of the total number of comments for each reliability level.

8.4 Discussion

8.4.1 General comments

The objective in analysing the comments provided by respondents was to validate the quantitative results of the survey using a second method, as well as to interpret more accurately the reasoning behind participants' responses to the questionnaire items. In addition, the comments section was intended to provide an opportunity for maintenance personnel to express their concerns regarding their workplace and discuss topics that had not been covered by the questionnaire items in Study 3.

Many of the sub-themes extracted from the comments and linked to form themes (Table 16) were similar to the most-frequently occurring factors from HFIT in Study 2. Numerous comments related to the themes of *Communication*, *Lack of information*, *Poor decision-making*, and *Equipment and spares*. As such, the comments analysis provided continuity between the conceptual framework developed in Study 2 and the quantitative data obtained in Study 3. In addition, despite consisting of only one open-ended question, the content analyses demonstrated that the comments provided a sufficiently rich source of data to test the conclusions from quantitative analysis of the questionnaire items and resolve ambiguous findings in the data. The results of the content analysis of comments were derived from a different method to that of the multiple-choice questionnaire, and so the two sources of data could be triangulated to determine if the findings from the questionnaire were supported or not. The following section explores the validation and interpretation of the quantitative results of Study 3 based on comments of maintenance personnel.

8.4.2 Qualitative data

The largest group of comments based on the four super-ordinate themes related to the *Efficiency of current work systems* (85 comments). This is a logical outcome from a question regarding aids and hindrances to one's work. The other super-ordinate themes related directly to reliability in the workplace, namely, *Communication and access to information* (45 comments), the *Need for more personnel and better workgroup support* (50 comments) and *Management and supervisory impacts on the workplace* (37 comments). These topics suggest that maintenance personnel are both aware of reliability-related factors in their workplaces, and able to articulate the way that human factors influence their assigned work.

Distinct differences in the proportions of several of these super-ordinate themes were found across work areas with different reliability levels (Figure 17). Maintenance personnel from middle and higher reliability work areas were more concerned about the current efficiency of their work systems, while the lowest reliability facilities were more concerned with the impacts on the workplace resulting from the decisions and actions of management and supervisors. However, no distinct difference appeared in the data from the other two super-ordinate themes, namely 1) organisational communication and the ability to access information, and 2) the need for better support for workgroups, including a need for more personnel. These results suggest that maintenance personnel working in the lower reliability work areas are concerned about decision-making imposed by management, while personnel from higher reliability facilities are voicing the need for greater efficiencies in the workplace. In contrast, the comments concerning information access, organisational communication, and better support systems were not necessarily associated with reliability level, but seemed to relate to endemic organisational phenomena which are experienced across all work areas. This result supports the contention in the previous chapter, that problems of communication and access to information within the company are organisation-level phenomena, manifested as an absence of significant group-level differences in *Job-related feedback* and *Information about change*.

As described in Chapter 7, two variables demonstrated significant group differences based on the reliability level of work areas. The content analysis derived from the comment data provided several findings that supported and several that contradicted the quantitative analysis. The following is a discussion of these two variables in relation to the comments analysis in order to extend the understanding of their association with reliability.

8.4.2.1 Problem-solving

The survey scale *Problem-solving* included items concerning task-related problems that had not been previously encountered, had no obvious answer, or required unique or creative solutions. In the analysis of comments, these dimensions appeared to be closest to the theme of *Poor decision-making*. One comment made was, “Our decision-making process is always too fast, I don't have enough time to think about decisions. One day we will make the wrong move due to poor planning” (Response #8). This relationship between perceptions of how problems are solved and decision-making may relate to the use of Recognition Primed Decision-Making (Lipshitz, Klein, Orasanu, & Salas, 2001) by maintenance personnel. Carvalho, dos Santos, and Vidal (2005) found that Recognition Primed Decision-Making underpinned 80% of the decisions made in an operational environment. The implication of this and other comments from Study 3 was that decisions were made by identifying the first solution that met situational criteria and was consonant with past experience. However, with the complexity of the facilities and reported shortage of specific procedures and information, the comments indicated that more advanced problem-solving skills would be required to support decision-making in maintenance activities. Thus, it is logical that more agreement with the requirements for *Problem-solving* is predictive of lower reliability. This interpretation was supported by the higher proportion of comments from low reliability facilities (Figure 17) in the super-ordinate theme *Management & supervisory impacts on the workplace,* which included the theme of *Poor decision-making.*

The responses to *Problem-solving* in the quantitative data may also be closely related to the theme of *Training needs & competency,* in that more training in methods of identifying maintenance solutions was considered necessary by respondents. A representative comment from a mechanical maintenance technician on a gas platform was that "Previous/ original employees of [the company] were given frequent training of equipment, ensuring competency. This has been reduced significantly leaving reliance on older staff" (#11). This demonstrated a focus on specific training and past experience, when better problem-solving strategies are needed to deal with complex maintenance tasks. Training needs and competency referred to in the comments were not the skills needed to be a competent mechanical fitter or an electrician, but rather a matter of acquiring the cognitive techniques to solve complex problems encountered with a wide range of equipment types. Supporting this, a contractor from the Process Plant with over ten years in the resource industry commented, "Information sessions before major shuts are handy. It helps to know the big picture" (#38). Although maintenance technicians are expected to acquire problem-solving and decision-making skills as part of their training, the diverse array of equipment which must be maintained in a typical petroleum installation means that specific experience, acquired over time, may not be sufficient for solving a wide range of potential problems. As a result, a positive response to *Dealing with problems not encountered before or having no correct answer* may represent a sense of needing better diagnostic skills (Cooke, 2002). Schaafstal, Schraagen, and van Berlo (2000) identified the lack of diagnostic skills as a deficiency in the training of technicians in the Royal Netherlands Navy. They were concerned that *engineering system knowledge* and a case-based approach to solving problems were taught to technicians, but that *general troubleshooting strategies* were not.

In terms of solving problems, a lack of training was compounded by the difficulty of obtaining information. "A fair bit of skill is involved in getting/ finding information on a certain piece of equipment …Could be made easier" (#131). The perception of a shortage of information related to the suppliers of equipment as well. "Better & more informative vendor manuals would be of great benefit," said a mechanical maintenance technician on an FPSO (#121).

Although much of the technical expertise and information required to repair numerous pieces of equipment would generally be managed through the supply of procedures, a number of respondents mentioned that more and better procedures were required. In the experience of a maintenance technician in the Process Plant there are "Very few procedures ... Information is available but hard to find" (#13). In addition, an Inlec on a gas platform with 10 years of industry experience said, "A good percentage of procedures are out of date/wrong and require updates. Changes are slow & require validating" (#116). The delays in up-dating procedures were regarded as a result of, "Poor management of change in regards to update of drawings, BOM's, procedures, etc. [making] simple tasks difficult. Existing and new procedures are inadequate and compromise safety" (#166). As identified in Study 2, lack of procedures and information contributed to assumptions and impeded problem-solving.

The use of specialist teams also impeded the development of this expertise, affecting the ability to solve problems. "With the use of Major Maintenance for a broad scope of work (and vendors) this impacts on the skill level of the Core Crew. This lack of knowledge then impacts the ability of the Core Crew to troubleshoot when equipment breaks down" (#112). In total, competency issues affected decision-making, which was also a frequent theme in comments relating to *Problem-solving*. An example was a comment about "continually repeating maintenance errors… Maintenance staff making decisions on equipment [when] they have no knowledge or understanding of its function" (#119). The relationship between problem-solving, decision-making and the development of competency was explained by Tucker, Edmondson and Spear (2002) in relation to nurses in the medical industry, working under similar constraints as maintenance technicians working in the petroleum industry. Tucker, Edmondson, and Spear found that constraints on fully solving problems limits the levels of expertise developed. The comments confirmed the quantitative findings of Study 3, namely that problem-solving was an important issue in reliability. In interpreting this, concerns about competency, access to information, and flawed decision-making were clearly among the main contributing factors according to maintenance personnel.

8.4.2.2 Design & Maintenance

The variable *Design & Maintenance* in Study 3 related to the original design of plant equipment, the adequacy of spare parts, and the current state of maintenance. These items were intended to determine if the perceptions of maintenance personnel regarding maintainability and maintenance effort in the plant influence the reliability level achieved by the facility.

Several concerns were raised in respondent's comments in relation to the design of their facility and spares parts. In terms of the original design, one maintenance technician considered that there had not been sufficient input from maintenance personnel, commenting, "We need to involve experienced maintenance people earlier in the design phase and equipment selection phase of new projects. We need to standardise equipment & configurations of systems across all facilities in the design phase" (#177). Cullen (2007) noted the lack of involvement in the design stage of maintenance personnel and other end users, resulting in "badly designed pieces of equipment [and] poor workplace or environments" (p.623). Relating to improving designs, *Management of change takes too long* was a sub-theme in the comments concerning the difficulty of modifying systems and equipment when maintenance technicians thought that modifications were required. This was included with the theme *Better work systems-workforce efficiency*. One comment was that, "It would help to have an engineer on board so that simple modifications or changes could be progressed. Getting changes/modifications through the system is very time consuming" (#108). Another maintenance technician commented, "Change [was] not rolled-out fully, sometimes very high level-you [the maintainer] fill in the gaps" (#26). Based on these opinions, it appeared that existing modifications were regarded by maintenance personnel as less of a problem than the inability to make changes when they are genuinely needed. This is partly an efficiency issue, and partly an effectiveness issue, as reliability depends on sufficient organisational learning to incorporate changes recognised by site-based workers (Cannon & Edmondson, 2005; Edmondson, 1996). That maintainability and the on-going requirements of maintenance were often not considered was one reason given for the high proportion of design-related failures in industry (Kinnersley & Roelen, 2007; Taylor, 2007).

In addition to the original design, the age of equipment also posed challenges as one maintenance technician commented, "Older machines and equipment [are] hard to find parts for" (#61). Seemingly, a greater perceived problem than the plant design is the lack of availability of spare parts and materials. Seven respondents offered comments such as, "Stock level of parts (are) very poor, and [it] takes too long to order and receive equipment" (#34). A reason given for this was that, "Quite often parts are either not catalogued, or are not in store, or are supposed to be on the shelf but aren't. Lead times on most components are excessive (>8 weeks)" (#129). Therefore, while design issues were more prominent in the interviews concerning failures, the availability of spares was a greater concern in relation to the impact of day-to-day maintenance tasks on reliability. Other *Design & Maintenance* issues were perceived to impact on the maintenance component of this variable, including lack of proactively attending to maintenance needs and the quality of vendor repairs and spare parts. Both of these are issues that arose in Study 2, and further link those findings to the findings in Study 3.

Regarding overdue maintenance, this was often reflected in comments concerning the shortage of maintenance personnel and spares. A maintenance technician on the least reliable FPSO wrote, "At the moment onboard [the FPSO] the main thing that gets in the way of maintenance is the lack of personnel. For the last few months there has been one fitter onboard as core crew to carry out maintenance" (#49). This and related comments indicate a tendency to operate in a breakdown mode of maintenance, which one maintenance technician identified as "Reactivity rather than proactivity" (#2). The dichotomy between the needs of production and maintenance requirements, in which management is "Not prepared to shut down equipment until it breaks down" (#119), is often an approach taken in manufacturing (Cooke, 2003). Even the potential for loss of production was considered grounds for delaying maintenance, as in the comment, "If there is any chance you may trip the process in order to do preventative maintenance then that maintenance may be delayed to a suitable day in the future" (#162). One of the principal tenets of contemporary maintenance engineering is that a preventive maintenance approach produces a more reliable system (Moubray, 1997). This was recognised by one maintenance technician: “Increasingly there is insufficient time for necessary planned work as breakdown maintenance consumes a considerable amount of my time. Job satisfaction has diminished as there is not enough time at the end of corrective work to document Lessons Learned and make some notes for 'similar' faults” (#149). Thus, the connection between a consistent approach to maintenance and reliability was clearly recognisable in the comments of the respondents, with recognition of the role of the shortage of resources, including personnel, spares, and planned maintenance time. This was captured by the super-ordinate theme of *Need for More Personnel and Better Workgroup Support Systems*.

8.4.3 Additional issues raised in the comments

In addition to the concerns of maintenance personnel which related to the items in the Study 3 scales described above, respondents also expressed opinions on additional themes. The most common of these themes included *Need For Better Work Systems-Workplace Efficiency, Management & Supervision, Lack of Information,* and *Procedures & Work Direction.*

8.4.3.1 Efficiency of current work systems

While the comments section of the survey was intended to provide information on workplace influences on reliability, judging by the large number of comments, efficiency of work systems was also important to maintenance personnel. Many of the comments related to the inefficiency of organisational systems, as in the comment, “Back log of permits that reduces the efficiencies of maintenance personnel to carry out work” (#86). Similarly, while modern workplaces typically attempt to operate with minimal staffing levels, there were nine comments relating to the need for specific support staff to be accessible. The most common expression of this was the need for planners and activity coordinators to be based in the off-shore work areas. Of particular interest was the disproportionate concern for efficiency in the middle and high reliability facilities, compared to the lower reliability work areas (Figure 17). One explanation is that maintenance personnel who can think in terms of more efficient methods may be better at solving reliability problems. However, this explanation is unlikely, as it relies on individual traits to explain group-level phenomena. A more plausible explanation is that staff in low reliability work areas were less concerned with efficiency compared to the need for improving reliability. This supports the conclusions of the quantitative findings, namely that plant designs and problem-solving difficulties are hindering lower reliability work areas. Achieving efficiencies are less of a concern for maintenance personnel struggling to maintain inherently unreliable equipment.

8.4.3.2 Management and supervisory impacts on the workplace

In contrast to efficiency of current work systems, management and supervisory impacts on the workplace was of greater concern to staff in lower reliability work areas. This super-ordinate theme included the theme of *Poor decision-making,* which was also disproportionately frequent in lower reliability work areas. As such, similar between-groups differences in reliability level would have been expected in the *Vigilance* variable, as it concerns decision-making (Mann, Burnett, Radford, & Ford, 1997). An explanation for the lack of significance in these results may relate to the differences in concepts between the items in the *Vigilance* scale and the concerns expressed in the comments. While the items in the *Vigilance* scale generally pertained to *individual*-level traits (e.g. "I consider how best to carry out a decision"), the comments mainly concerned *group*-level flaws in decision-making, such as, "Maintenance staff making decisions on equipment [when] they have no knowledge or understanding of its function" (#119), and *organisation*-level flaws, such as, "Disagree with most decisions [the company] makes how to do my job" (#101). As well as indicating that the measure selected was inappropriate, and that hypothesis H_2 might still be valid, this finding also indicated the importance of considering level criteria (individual, group, or organisation) when selecting measures for human factors research.

8.4.3.3 Communication and access to information

The super-ordinate theme *Communication and access to information* was found to be relatively consistent across all reliability levels (Figure 17). As such, the measures *Job-related feedback* and *Information about change* were unlikely to detect group-level differences based on reliability. Instead, the quantitative and qualitative data in Study 3 provided information concerning the communication climate across the organisation. In addition to clarifying the reason for a lack of significance in the data from the *Job-related feedback* and *Information about change* scales, the comments provided a further link to the findings in Study 2. Thus, organisational communication was reflected in the themes of *Lack of information* and *Procedures & work direction.*

The theme *Lack of information* mainly concerned the principal source of information for maintenance technicians, namely the SAP database, which provides work orders, Bills of Materials (BOM), and maintenance history data. Although many comments related to the need for more SAP training and a general dislike of using it, most comments related to the difficulty of locating required information. In keeping with most modern operations, much information is provided electronically (Baltes, Dickson, Sherman, Bauer, & LaGanke, 2002). However, this appeared to create difficulties for workers whose principal work is not computer-based, resulting in "Too much focus on SAP & not enough on the actual job" (#119). As one maintenance technician noted, "I find the bulk of info is on the intranet, SAP, etc, however, I often give up as I cannot locate it in search fields, etc." (#29). The software itself is partly blamed due to the "unnecessary complexity of SAP compared to other CMMS [Computerised Maintenance Management Systems] I've used previously" (#183).

Partly this could be improved through improving systems and better training, that is, the "SAP system needs to be revised in regards to specific training in small groups for personnel who use SAP for maintenance. Information transfer from supervisors, SAP group to maintenance personnel need to be improved" (#142). The entry of more reliable data in SAP is also required, as several respondents observed that "SAP BOMs [are] not populated. Critical spares for all equipment [are] not correctly catalogued and BOMed [*sic*]" (#180). Difficulties in obtaining computer-based information were not limited to SAP, with vendors also not facilitating on-line access to critical supporting information, as indicated by the comment, "Better & more informative vendor manuals would be of great benefit (#121)". Even when it is available, accessing the information suffers from the same problems as SAP, in that "Vendor info not easy to find due to the way it's been loaded into DRIMS [the company's document retrieval system], e.g. PDF docs of 100+ pages & no indexing function (#165)."

Another issue that arose in Study 2, and was reflected in the comments was the theme of *Procedures & work direction*. Accurate procedures are regarded as critical to reliable maintenance work (Dekker, 2003a; McDonald, Corrigan, Daly, & Cromie, 2000). In the opinion of maintenance personnel, “More job procedures [are] required” (#15), and “A good percentage of procedures are out of date/wrong and require updates. Changes are slow & require validating” (#116). This appeared to be a systemic issue that was recognised by maintenance technicians as impacting on efficiency and reliability, and ultimately safety: “Poor management of change in regards to update of drawings, BOM's, procedures, etc. makes simple tasks difficult. Existing and new procedures are inadequate and compromise safety” (#166). From the interviews in Study 2 it was reported that numerous procedures exist pertaining to Operations activities, but in contrast it was commented that, “Maintenance procedures are very poor” (#186). It is unlikely that maintenance reliability can be supported without addressing the concerns and experience of maintenance technicians regarding access to adequate, accurate work-related information. However, this appears to be an issue that is not apparent in group-level differences, and therefore requires investigation at the organisation-level.

8.5 Summary and Conclusions

The data obtained through content analysis of respondents’ comments served to triangulate the quantitative data obtained in Study 3. That is, it provided both support for the significant results of the quantitative findings, and possible explanations for the non-significant findings. The two variables in Study 3 that significantly differentiated high and low reliability work areas were based on the perceptions of maintenance personnel regarding the design and maintenance of their workplace, and their ability to solve problems that arise. In their comments, *Design & Maintenance* was perceived by maintenance personnel as influencing reliability principally through the quality and availability of spare parts, and the maintenance condition of their facility. Little mention was made of the original design of equipment, other than one comment concerning the need to involve maintenance personnel in designing plants. A concern with plant design may only arise when a failure occurs; otherwise maintenance technicians tend to ‘work with what they have.’ The role of the *Overdue maintenance* dimension in the *Design &*

Maintenance scale appeared to be supported by comments made concerning the shortages of time, personnel, and spares needed to manage maintenance requirements. At the same time, there were a number of concerns with the effectiveness of maintenance planning, with a frequent request to have maintenance activity planners onboard off-shore facilities.

Many comments concerning *Problem-solving* related to access to adequate technical information, including up-to-date procedures, often expressed as 1) the difficulty of obtaining information from electronic information systems such as the SAP database, and 2) the shortage of up-to-date procedures with required technical information. Similarly, sufficient technical training and the acquisition of experience were seen to be hampered by workplace systems. These systems in turn impacted on decision-making, which was also identified by maintenance personnel as flawed at times. They regarded these flaws as being due to organisational pressures such as time constraints, organisational culture, and problems with the information systems that were designed to ensure that learnings are fed back in order to assist in solving new problems. Comments concerning decision-making related mainly to the group-level and organisation-level, rather than the individual-level. As the items in the *Vigilance* scale were expressed in terms of individual-level traits, this may be an explanation for the absence of a significant between-groups difference. This finding highlighted the importance of investigating level-specific phenomena in human factors research using measures that are appropriate to the level being investigated.

The single largest group of comments discussed the efficiency of current work systems. While these comments did not directly concern the reliability of equipment, they did indicate that maintenance personnel, particularly in the middle and highest reliability work areas, are concerned about inefficiency and have a negative perception of workplaces that are not structured in a way that facilitates their work. This implied that in work areas in which reliability was higher, maintenance personnel had a greater sense of motivation, and commitment to solving problems and improving their workplace systems. In lower reliability work areas, maintenance personnel appeared to have less sense of control over their workplace, and consequently their focus was on management and supervisory impacts on workplace systems, including the effects of poor decision-making.

Finally, in keeping with the conclusions of Study 2, organisational communication was found to be a frequent concern to respondents. Much of this concerned the difficulty of accessing information through the electronic information management systems, and the lack of, and inaccuracies in, procedures for maintenance activities. These concerns were expressed with relatively equal frequency across lower, middle and higher reliability work areas, indicating that inadequate information is an organisation-wide phenomenon. The uniform concern across all reliability levels was therefore a possible explanation for the absence of significant group differences observed in the scores for *Job-related Feedback* and *Information about change*.

Respondents used the opportunity of the survey to express their opinions concerning facets of the workplace that helped and hindered their work. Thus, while not all comments were relevant to this research, judging by the large response received, maintenance personnel clearly appreciated the opportunity afforded by the survey to articulate their opinions concerning their workplace.

9.0 Overall Discussion

9.1 Introduction

In Chapter 1, the concept of reliability as an important dimension of industrial activity was presented. Although, reliability is generally conceptualised in terms of technical design and engineering failure analysis, the value of incorporating a human factors approach was proposed on the basis of advances in understanding the role of human factors in hazardous industries, such as petroleum production. Chapter 2 reviewed the literature relating to the fields of engineering reliability and human factors, with particular emphasis on:

- the limitations of a solely engineering approach to reliability
- the theoretical and empirical research that has been conducted into the relationship between human factors and maintenance performance in the petroleum industry
- models of failure based on flaws in systems for organising maintenance activities
- the importance to human factors theory of the concept of level-specific phenomena in organisational reliability.

Chapter 3 explained the rationale for designing a study to identify the predominant human factors in failures, and determining the quantitative relationships between human factors and the maintenance reliability of petroleum industry operations. Both the practical value to industrial organisations and the theoretical contribution to understanding the role of human factors generally in the workplace were considered. Chapters 4-8 then detailed the methods and findings of three studies conducted within a petroleum producing company to improve the understanding of these relationships. The research in these three studies was based on the following objectives of the project:

- Select and refine a method for analysing the most-frequent contributors to maintenance failures, and use this method to determine the human factors that appear most frequently in company-based reports of maintenance-related failures.

- Determine the human factors that contributed most-frequently to maintenance-related failures in petroleum industry operations based on structured interviews with maintenance personnel.
- Measure the group-level differences between higher and lower reliability work areas in the strength of the human factors that were most frequently identified in Study 2 as contributing to maintenance-related failures.

In this chapter, the key findings from these studies are presented. The strengths and limitations of the data collection methods and sample populations used are explored in order to suggest improvements in methodology. Following this, the theoretical and practical implications of this research in terms of the reliability of petroleum industry operations are examined. Finally, future directions are considered for further human factors studies of maintenance reliability in the petroleum industry.

9.2 Key Findings

9.2.1 Findings in Studies 1-3

Figure 18 provides a schematic representation of the conceptual links between the human factors found to be important in the findings of Studies 1-3. In Study 1, reports of Asset Damage/Production Loss incidents (N=194) were analysed to determine the demographics of maintenance-related failures within the company. *Violations, Design & Maintenance, Detection,* and *Decision-making* were identified as the four most-frequent causes, respectively, attributed to these incidents. These findings accord with a view of failure in industrial systems as either technical in nature (Dhillon, 2002), or caused by violations of workplace rules (Lawton, 1998) and human errors, often characterised as a loss of situation awareness (Cacciabue, 2004) or poor decision-making (Hobbs & Williamson, 2002). Using HFIT (Gordon, 2001), a mean of 2.3 factors per incident were identified in the incident reports. A more detailed examination of the group-level (Crichton, 2005; Culvenor, 2003) and organisation-level (Dekker, 2006) contributors to failure was considered necessary to better understand the role of human factors in reliability.

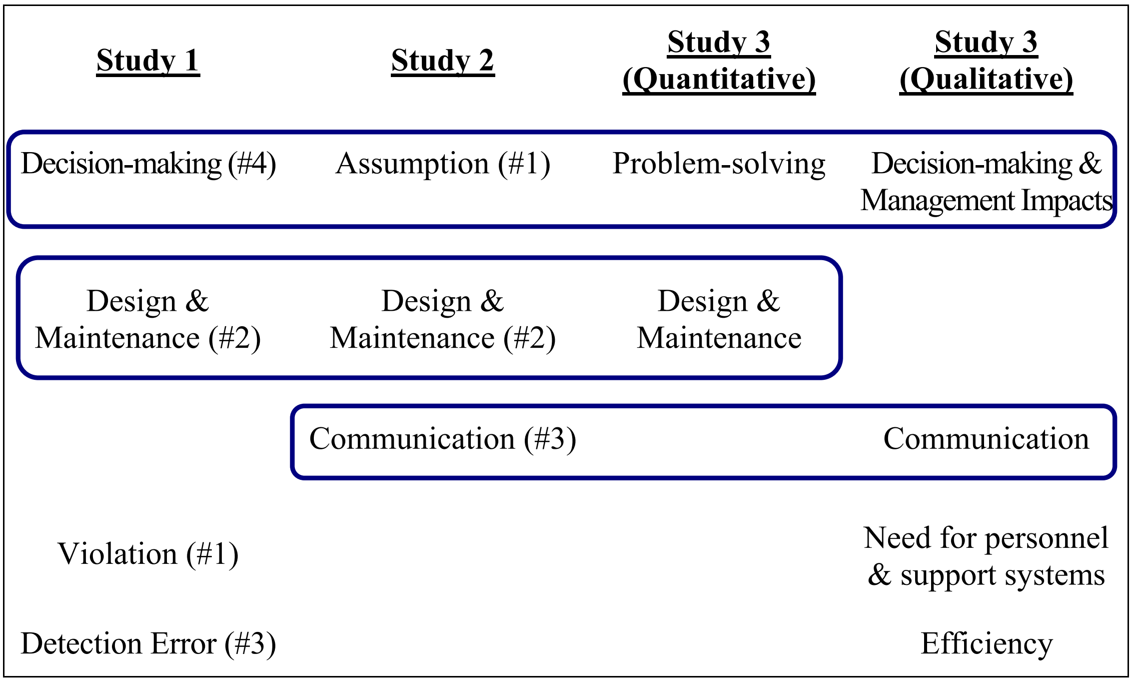

Figure 18. Diagram of conceptual links between the findings from Studies 1-3.

Study 2 provided this greater depth of understanding of the contributors to failures through information collected in structured interviews (N=38) with maintenance personnel, concerning failures they had personally experienced. In these investigations, again using HFIT, a mean of 9.5 contributing factors per incident was identified. *Assumption, Design & Maintenance,* and *Communication* were identified as the three most-frequent human factors codes, respectively. In addition to identifying these recurring contributors to failure, the discussions surrounding each of the factors in HFIT (k=27) provided detailed supporting information, which was used to identify the sub-factors influencing each incident. For example, these sub-factors clarified that flaws in *Design & Maintenance* were mainly related to limited access for maintenance, poor labelling of units, problems encountered with modifications and non-standard designs, and overdue maintenance. Similarly, *Assumption* was found to be partly the result of problem-solving behaviours, such as making assumptions based on past experience, partly flawed decision-making, and partly the result of inadequate task-related information. The most-frequent *Communication* sub-factors represented a lack of communication, and poor communication between companies or team members, or between on-shore and off-shore personnel.

The identification of sub-factors was useful in the process of selecting measures for the survey for Study 3. Based on the results of Study 2, the measures for Study 3 consisted of the *Vigilance* scale from the Melbourne Decision-Making Questionnaire (Mann, Burnett, Radford, & Ford, 1997), the *Problem-solving* scale from the Work Design Questionnaire (Morgeson & Humphrey, 2006), and the *Source of Information* and *Subject of Information* scales from the OCD/2 questionnaire (Wiio, 1978). In addition, the eight most frequent *Design & Maintenance* sub-factors identified in Study 2 were selected for the Study 3 *Design & Maintenance* scale.

A survey form was sent to maintenance personnel across nine work areas in three types of facility, with each work area assigned a reliability level relative to the other areas within its facility type. Analyses of variance and covariance of the survey and reliability level data from valid responses (N=172, Response rate = 41.6%) revealed that statistically significant group differences between work areas were found to be based on reliability level for *Design & Maintenance*, and *Problem-solving*, but not for the other three variables. Higher reliability was predictive of higher *Design & Maintenance* scores, while lower reliability was predictive of higher *Problem-solving* scores. A significant interaction effect was observed between reliability level and facility type for the dependent variable *Design & Maintenance*. In addition, there were significant correlations between *Design & Maintenance* and *Time at Facility*, and between *Job-related feedback* and *Employer*.

Of the survey respondents, 101 (56.7%) supplied written comments in response to an open-ended question at the end of the survey form that asked what they considered to have hindered or helped their maintenance activities. Using Interpretative Phenomenological Analysis, 57 sub-themes were identified in the text, which were reduced to 12 distinct themes, and ultimately four super-ordinate themes. Of these super-ordinate themes, *Communication & access to information,* and *Need for more personnel & better support systems* were uniformly represented across lower, middle and higher reliability work areas. Contrasting this, comments concerning *Efficiency of workplace systems* were more frequent in middle and higher reliability work areas, while respondents from lower reliability work areas commented more frequently on *Management & supervisory impacts.* This super-ordinate theme included the theme of *Poor decision-making,* which was also more frequently mentioned in comments from lower reliability work areas than middle or higher reliability work areas.

The following is an examination of the strengths and weaknesses of the methods used to obtain these findings in the three studies conducted.

9.3 Strengths and Limitations of the Present Research

9.3.1 Strengths

9.3.1.1 Methodology

This research was one of the first studies to utilise multiple sources of data to develop a quantitative analysis of the relationship between human factors and plant reliability. Quantitative and qualitative experimental methods, triangulation of data sources, and both engineering and organisational data were used to test a methodology for assessing the influence of human factors on reliability. The agreement among findings has demonstrated the advantages of triangulating the data from multiple collection methods, as has been used effectively in related research areas (Glendon & Litherland, 2001; Oedewald & Reiman, 2003). Each of the methods, namely company incident investigations, HFIT interviews, surveys, and content analysis, has contributed additional data concerning the role of human factors in maintenance activities. At the same time, triangulation has been useful when the findings of one method were needed to interpret or support the findings derived from another method.

In addition, these methods demonstrated the ability to provide significant conclusions regarding the role of specific factors in a specific domain, namely petroleum operations. The research demonstrated that rich sources of data are available from company incident reports, structured interviews, and the perceptions of maintenance personnel, which could be used to investigate empirically human factors theory. The findings demonstrated that there is a need for greater human factors expertise in investigating incidents in petroleum operations, as well as a need to distinguish between the important factors in day-to-day reliability and those in failures. The research also demonstrated that these methods could be utilised to obtain baseline data on the human factors climate or 'health' of an organisation in relation to reliability. Then, by using longitudinal studies, these methods have a potential application for determining whether deterioration or improvement is occurring over time, and for measuring the effects of interventions by management.

Finally, the research demonstrated the value of eliciting the opinions of the maintenance workforce in order to improve knowledge about the condition and operation of facilities, as well as to obtain explanatory data to develop and evaluate theory. Maintenance personnel showed a willingness to provide information that was useful for research purposes. They also demonstrated an awareness of existing conditions that was sensitive to the operational differences between work areas. Although surveys have been commonly used to elicit opinions concerning the influence of individual traits and organisational factors on organisational performance, this was one of the first studies to rely on the perceptions of maintenance personnel as the primary source of quantitative data concerning plant design and maintainability. The statistically significant relationships demonstrated among group and organisation variables justified this confidence in the value of their perceptions.

9.3.1.2 Demonstrated human factors in reliability

The current research has demonstrated potentially important understandings concerning the significant role of *Design & Maintenance* in reliability, and more importantly, the significant requirements of problem-solving and information availability. These findings might assist decision-makers with respect to specifying the design of workplace (e.g., training, supervision, and procedural requirements) in the early stages of engineering new facilities, as well as providing a basis for remedial interventions to correct the contingencies of flawed designs in existing facilities.

9.3.2 Limitations

The research suffered from a number of limitations relating to the methods used for data collection, and the size and composition of the sample populations contributing to Studies 2 and 3.

9.3.2.1 Method

The HFIT instrument provided a comprehensive taxonomy, comprising many of the workplace factors influencing performance that were described in the human factors literature reviewed. As such, it seemed suitable for determining the most-frequent contributors to failure. Nevertheless, HFIT required modification to improve its effectiveness and accuracy for obtaining the required information for Studies 1 and 2. Despite these modifications, a number of limitations were apparent with the methods used to collect data for Studies 1 and 2. The limitations in using company incident data were anticipated, as discussed in Section 4.4, and the data was recognised as being of only limited value. The following limitations arising in the use of HFIT to collect data in Study 2 were more critical to the outcomes of this research.

- Despite the modifications made to HFIT, there was still a degree of ambiguity in the names and sub-factors of several codes, introducing unnecessary variability in assigning codes to failures. This might be resolved by further refinement of code names and sub-factor questions, followed by validation using more than one rater.
- Assignment of codes relied on accurate recall of events some time after they occurred, with biases developing in the interviewees' accounts of events. Stipulating that only recent events be investigated could provide better recall and may also reduce hindsight bias.
- Use of a single coder was useful in maintaining consistency across the group of interviews, but provided no means of eliminating the interviewer's biases in interpreting events and actions. This was partially addressed by enlisitng a second coder for a random selection of cases, and recoding all cases at the end of interviewing to reduce drift in coding. However, coding consistency could be improved by using multiple coders for all cases and monitoring the inter-rater reliability.
- McNemar Tests of Change showed no significant differences between closely ranked codes, despite the Cochran's Q Test which indicated that significant differences existed within the dataset. The most serious implication of this is that the most-frequent codes, *Assumption*, *Design & Maintenance,* and *Communication*, which were accepted as the basis for Study 3, were not necessarily more important than the codes following them in ranking. A less

serious implication was that there was insufficient statistical power in Study 2, and that with a larger sample size, significant differences may be detected.

There were a number of limitations to Study 3, involving both assignment of reliability level and collection of data concerning the perceptions of staff.

- Reliability ranking depended on production deferments, which were relatively infrequent events in some work areas with a degree of variability from month to month. More precision in assessing the reliability of facilities would increase the confidence in these rankings as well as allowing for regression analysis between a scalar reliability variable and survey scores. This precision could be achieved through analysis of Mean-Time Between Failure data from major pieces of mechanical and electrical equipment (e.g., programmable logic controllers, compressors, turbines, and pumps). This type of failure data is currently recorded by the company, but needs to be collected more systematically and recorded more accurately to be of value in measuring work area reliability.
- Although comparisons among the same type of facility (gas platforms or FPSOs) eliminated some confounds, comparing different work areas in the Process Plant was more problematic, as different types of equipment and maintenance processes are involved. Cognitive task analyses could assist in ensuring that the tasks being done in different work areas are accounted for in any comparisons.
- Selection of scales appropriate to the factors identified in Study 2 relied on the availability of validated measures in the literature. The most appropriate scales were selected, but there were clear inadequacies in several of these in terms of testing the constructs of interest. For example, while testing of the prevalence of assumptions in decision-making at the group-level was required, the *Vigilance* scale items referred to individual-level traits. This evoked a relatively uniform and positive response, which did not accord with many of the comments made in Study 3 relating to group-level characteristics of decision-making. Similarly, the items in the communication scales often referred to organisation-level processes (e.g. information on organisational change), when testing of group-level differences was required. Access to validated scales other than those in the public domain may provide a broader

selection of instruments for testing the human factors constructs identified in Study 2.

- Factor analysis has revealed some disparities in the loadings of items relative to the original scale structures of *Design & Maintenance* and *Organisational Communication.* Again, this may require better scale selection to improve validity with respect to the constructs being tested, or may require refinement of the individual items and consistency testing of these revised scales to ensure internal reliability.
- Despite expectations based on the literature, *Organisational Communication* and *Vigilance* did not demonstrate a significant relationship to reliability. Explanations were offered based on content analysis of the comments made by survey respondents. However, these responses were not rigorously tested, and questions remain as to whether *Organisational Communication* and *Vigilance* scores could be predictive of reliability if measured differently (e.g., more sensitive measures, more statistical power, or a different form of analysis). More detailed testing of these dimensions is required to understand this lack of significance in the survey results.
- Some of the conclusions of this research were drawn from content analysis of a single open-ended question. While the responses provided a rich source of data, there was clearly a frequent focus on *efficiency* of maintenance processes, when reliability, the construct being tested, is more concerned with the *effectiveness* of these processes. Questions more clearly focussed on effectiveness would provide data more specific to the overall aim of the research, namely understanding the relationship between human factors and maintenance reliability.

9.3.2.2 Sample size

Small sample size was a recurring limitation in Studies 2 and 3. In Study 2 the availability of maintenance personnel willing to take time out for an interview and the remoteness of facilities limited the number of potential participants available for interviews. Sample size was also limited due to the time required for structured interviews, which in turn made achieving sufficient statistical power in the study difficult. The lack of statistical power may have been a reason for the inability to find significant differences between closely-ranked codes in Study 2. Multiple interviewers, also serving as multiple coders, would expedite the collection and processing of interview data, possibly revealing a significant difference in the frequency of the predominant codes.

In Study 3, the overall population size was considered acceptable (Tabachnick & Fidell, 2007), but the number of responses from several facilities provided a sample that was too small for the intended analysis. Thus, the 3x3 factorial design, as originally intended with facility type and reliability level as the independent variables, was not possible. Again, statistical power was low for the analyses that were conducted, possibly contributing to the non-significant results obtained from ANOVAs of several of the variables. Replicating the research in a larger maintenance organisation or by including additional personnel, such as operators, may provide a clearer evaluation of the hypotheses being tested.

9.3.2.3 Selection bias

One of the consequences of small sample sizes was the possible introduction of selection biases. The cohort for the interviews was self-selected on the basis that all who offered to be interviewed were accepted for interviews. This resulted in the sample being less representative on some criteria, relative to the entire company workforce. For example, the sample was biased towards maintenance personnel who worked in the head office and the Process Plant, who were easier to access than personnel who worked off-shore. With a large enough workforce and more access to off-shore facilities, a more representative sample could be obtained. Similarly, the incidents examined were self-selected by the participants. This sample was also less representative on several demographic criteria, relative to the incident population in the company database used in Study 1. For example, severe incidents were found to be over-represented in the interviews. This could be corrected through selection of representative incidents and interviewing the people involved. However, this requires targeting individuals, which then leads to concerns about trust and confidentiality, which were not encountered when the interviewees were self-selected.

In Study 3, selection bias mainly resulted from motivational differences in completing the survey, and in lodging comments at the end of the survey. It is possible that the 42% of the maintenance personnel who completed a valid questionnaire were more motivated than the other 58%. The survey results may have been biased if, as is likely, less-motivated staff held different opinions relating to the variables tested in the survey. A data collection method that achieves a higher response rate, such as a telephone interview sample, may provide an indication of the representativeness of the responses obtained.

Finally, as the research was only conducted within one organisation, it is difficult to generalise the findings across other organisations and other industries. Replicating the studies in other petroleum operations and other industries would indicate the applicability of the findings across different domains.

9.4 Theoretical Implications

The current research makes an important contribution from a methodological and theoretical perspective to understanding the role of human factors in reliability, supporting many of the ideas expressed by researchers into organisational performance. Research in the areas of aviation, nuclear power generation, medicine, and military operations has supported the notion that high reliability can be developed in existing organisations through a human factors approach (Ericksen & Dyer, 2005; Vogus & Welbourne, 2003; Klein, Bigley & Roberts, 1995). The current research has contributed an understanding of the theoretical role of human factors in a distinctly different domain, namely the petroleum industry. Through the derivation of empirical group-level measures for workplace-based studies, Studies 2 and 3 have revealed a new theoretical perspective on the way that human factors interact with the design of physical facilities to influence the reliability of outcomes.

9.4.1 Assumptions/Problem-solving

The results of this research revealed that an integrative approach including both design and problem-solving measures was beneficial in understanding the impediments to performance in socio-technical systems. While logic dictates that these two should be related, as design in itself is a form of problem-solving (Wilpert, 2007), the challenges of investigating across different knowledge domains, i.e. engineering and psychology, coupled with the format differences between technical data and socio-metric data, have limited the research in this area. The current studies have demonstrated the ability to combine technical assessments of equipment performance with the human experience of working with this technology, providing a more comprehensive basis for organisational decision-making. In particular, problem-solving data demonstrated that equipment and workplace design limitations were significantly related to the requirements for problem-solving in the workforce. The negative correlation between *Design & Maintenance* and *Problem-solving* suggested a moderating role for problem-solving on the effect that design and maintenance factors have on reliability outcomes. In comments from maintenance personnel, *Design & Maintenance* considerations were rarely mentioned, while comments were frequently received concerning decision-making and problem-solving. These latter comments were more frequently received from low reliability work areas (Figure 17). These differences demonstrated a need to provide support for organisational decision-making and problem-solving in order to facilitate reliable maintenance of inherently flawed technical designs.

In turn, the human factors and organisational psychology literature reviewed in Section 2.9 has clearly recognised problem-solving and associated decision-making as fundamental group-level processes that influence organisational outcomes. Oedewald and Reiman (2002; 2003) in particular characterised these dimensions as critical demands of the maintenance core task. The current research extended these theoretical developments by demonstrating a quantitative and significant inverse relationship between problem-solving and maintenance outcomes. This research also extended current theory by postulating how problems were being solved, namely through use of Recognition-Primed Decision-making, at times with assumption-making based on experience and heuristics. Decision-making observed in Study 2 accorded with Carvalho, dos Santos, and Vidal's (2005) estimate that 80% of the decisions made in the operating environment that they investigated were made through a Recognition-Primed Decision-making process. However, the current research suggested that a Recognition-Primed Decision-making mode of problem-solving defaulted to assumptions when provoked by shortages of time and information, and by complexities in the problem space (e.g. equipment, the work environment, or work systems). As a result, the assumptions associated with this process were the most frequently occurring contributors to the failures examined in Study 2.

Although the literature rarely discussed 'assumption-provoking' factors *per se* in organisational behaviour, two of the cognitive processes involved, problem-solving (Proctor & Van Zandt, 1994) and decision-making (Kerr & Tindale, 2004) were often recognised as the stages at which assumptions were made, and these were often considered in the human factors literature in relation to organisational reliability. For example, Ericksen and Dyer (2005) discussed 'diligence' in locating and identifying the source of problems, while other HRO literature (Choo, 2008; Vogus & Welbourne, 2003) suggested the need to avoid over-simplifying problems, both of which will reduce the tendency to make assumptions. In the case of decision-making, methodicalness has been recognised as part of the core maintenance task (Oedewald & Reiman, 2002), as has the importance of vigilance in the cognitive processing (e.g. acquiring information and assessing alternatives) needed for successful decision-making in the workplace (Hodgkinson & Healey, 2008; Lipshitz, Klein, Orasanu, & Salas, 2001). For maintenance personnel, flexibility in adapting strategies to correct problems was suggested by Pettersen and Aase (2007), and this is another approach that might reduce the dependence on assumptions.

It was anticipated that both of the dimensions of problem-solving and vigilance in decision-making would have demonstrated a relationship with group differences in reliability level. However, only the *Problem-solving* scores were significantly predictive of reliability at the group level. The results of the content analysis of Study 3 comments (Figure 17) indicated that respondents in lower reliability work areas were more likely to mention decision-making (i.e. as a sub-set of *Management & supervisory impacts)* than those in middle and higher reliability work areas. Attitudes to group- and organisational-level decision-making were typified by the comment, "*Our* decision-making process is always too fast [italics added]," indicating that decision-making variables would be expected to be predictive of group differences. Zohar and Luria's (2003b) studies of supervisory impacts on workgroup climate indicated the important mediating role of supervisors in workgroup climate as perceived by workers. It appeared from their research and the comments of maintenance personnel in the current research that understanding vigilance in decision-making in the current context requires examination of decision-making at the level of work teams, supervisors and management (Kerr & Tindale, 2004). Thus, the level of analysis implied in the wording of the *Vigilance* scale may have been the main factor in the absence of a relationship between vigilance in decision-making and reliability level. The items in the *Problem-solving* scale inquired about characteristics of the maintenance work in the respondent's group (group-level) while, the *Vigilance* scale was designed to measure the respondent's personality traits (individual level) with respect to decision-making. The former were more likely to detect group differences in job design and workplace climate (Bourrier, 1996; Tucker, Edmondson, & Spear, 2002) while the latter may only detect differences in commitment (Louche & Lanneau, 2004; Meyer, Becker, & Vandenberghe, 2004) and motivation (Cassignol-Bertrand, Baldet, Louche, & Papet, 2006; Latham & Pinder, 2005). These differences between the items in *Problem-solving* and *Vigilance* in detecting group-level reliability differences accord with the current interest in accurately assessing organisational phenomena at the appropriate level (Culvenor, 2003; Torp & Grøgaard, 2009; Zohar, 2008; Zohar & Luria, 2005).

In contrast to *Vigilance*, *Problem-solving* demonstrated a significant, but inverse, relationship to reliability level. Thus, as the assessed reliability decreased, the apparent need for better problem-solving skills increased. From the results of Study 2, insufficient problem-solving skills, in conjunction with poor designs and insufficient information, appeared to be accompanied by assumption-making, which was the principal contributor to failures. Thus reliability, problem-solving skills, and maintenance failures were at least empirically linked through the two studies. Directionality still remained an important question to resolve. That is, the question remained whether a lack of problem-solving skills requiring more frequent assumption-making causes lower reliability, or whether facilities that by history or design tend to be more unreliable require personnel to develop better problem-solving skills. Aside from the unlikelihood that less-skilled maintenance technicians and supervisors had been employed in lower reliability facilities, the evidence indicated that it is more likely that low reliability facilities require better problem-solving skills. *Problem-solving* scores showed a significant negative correlation with *Design & Maintenance*. As scores on *Design & Maintenance* increased, perceptions of the need for problem-solving skills decreased, implicating problem-solving as moderating the effects of workplace design on reliability outcomes. This was consistent with Bourrier's (2005) contention that technical design should be accompanied by organisational design. The provision of skills, and systems for resolving problems as they arise, has been demonstrated to have a substantial influence on reliability differences among similar manufacturing operations (MacDuffie, 1997).

Furthermore, the results of the content analysis of comments demonstrated that management and supervisory influences are perceived by maintenance personnel, particularly in low-reliability work areas, as having a major impact on their workplace. Whether due to poor maintainability of the original design, or historical neglect of maintenance requirements, the 'creation' of inherently low-reliability facilities through design and management decisions then appeared to generate a need for greater problem-solving resources in the workforce. If maintenance technicians in low-reliability work areas then cannot access the problem-solving skills, systems, and information required, their alternative is to rely on assumptions to fill in the cognitive gaps. This is analogous to the situation for nurses, as was described in studies of US hospitals (Edmondson, 1996; Tucker, Edmondson, & Spear, 2002) in which shortages of resources, or internal organisational politics resulting from management decisions, tended to drive workers towards relying on assumptions rather than rigorous problem-solving. Edmondson argued that the need for solving underlying problems in turn requires greater support from and involvement of management. This conclusion was supported by comments in the theme of *Management & supervisory impacts*, such as the one identifying a "management focus on maintenance costs without any understanding of what contributes to these costs" (Respondent #70).

The issue of problem-solving requirements also related to the modes of cognitive processing applied to resolving equipment faults. As mentioned, the relative frequency of assumptions, as compared to other failure codes, was consistent with a tendency of maintainers to adopt Recognition-Primed Decision-making. Although this form of Naturalistic Decision-making is now recognised as a common mode of decision-making among experienced workers in operating facilities (Lipshitz, Klein, Orasanu, & Salas, 2001), defaulting to Recognition-Primed Decision-making may be problematic in facilities in which the experience levels and inherent reliability are low. In Recognition-Primed Decision-making, the first alternative that accords with previous experience and decision-making criteria is adopted as the required solution, particularly under time and internal political pressures (Sagan, 1994). Deficiencies in this approach are aggravated by the occurrence of organisational 'blind spots' to information that does not fit the prevailing frame of reference (Choo, 2008). Thus, where complexity is low, inherent reliability is high, and experience is high, Recognition-Primed Decision-making is arguably an efficient mode of problem-solving (Klein, 1997). Efficiency as an objective of maintenance personnel was clearly demonstrated in the comments they made. However, where reliability is low for a particular facility, complexity is high as in the petroleum industry, and experience varied, as *Time at Facility* (Figure 11) and *Time in Industry* (Figure 12) demonstrated, requisite variety in cognitive abilities, such as problem-solving skills (Hollnagel, 2002), may be insufficient to support a Recognition-Primed Decision-making approach. The result is likely to be a process of more assumption-making, leading to incorrect solutions, and an increased probability of failures. Under these conditions, a more analytical approach to resolving maintenance problems may be beneficial. Schaafstal, Schraagen, and van Berlo (2000) recognised that training of maintenance technicians tended to be experience-based as opposed to being based on problem-solving skills development. They argued for more emphasis in training programs on learning trouble-shooting strategies rather than on systems knowledge.

Klein (1997) also recognised that the Recognition-Primed Decision-making model did not apply to all Naturalistic Decision-making situations, and that a more analytical approach, involving identifying and comparing alternatives, could still occur in Naturalistic Decision-making. Experience and heuristics would still play a major role in workplace decisions, but a more thorough gathering of information and exploration of alternatives would be developed. This accords with Rasmussen's (1997b) view of Naturalistic Decision-making as operating differently at different cognitive levels (i.e., the rule, skill, and knowledge levels) and the need to clearly distinguish the level of cognition involved when considering appropriate designs for workplace systems and training. The evidence in this research is consistent with a moderating role for *Problem-solving*, in which any inherently low reliability in designs may require a different level of problem-solving skills and information availability, in order to both improve day-to-day outcomes and reduce the probability of failure.

9.4.2 Design & Maintenance

The consistency of *Design & Maintenance* across all three studies (Figure 18) demonstrated the influence that this factor has on reliability. It was understood from a number of points of reference, including that of company investigators and maintenance personnel discussing both past events and current workplace conditions. That original designs and the ease of maintaining these designs has influenced both failures and day-to-day reliability is well-supported by the literature. The role of engineering design in failures has been acknowledged in past research, but explaining its role in day-to-day performance has been less clear. For example, Kinnersley and Roelen (2007) have shown that 51% of the accidents in aviation and 46% of accidents in NPPs relate to design. Specifically in the process industries, Taylor (2007) attributed 55% of accidents to design. In Study 2, 49% of the incidents related to design issues, which agrees well with both Taylor's and Kinnersley and Roelen's data.

Despite detailed data on the genesis of accidents, no data were supplied in either of the two investigations cited above that indicated the relationship of day-to-day reliability to design. This may be due to, as Wilpert (2007) argued, "complex technologies and large-scale technical installations [being] seen to fall into the domain of engineers who traditionally tended to focus on component failures" (p.295). Tjiparuro and Thompson (2004) also discussed the determination of maintainability based on failure-based techniques, but argue that a more "holistic treatment of maintainability requirements" (p. 105) is needed, along with more consistent evaluation methods. Attempts have been made to devise such evaluation methods (Mason, 1990; Wani & Gandhi, 1999; International Standards Organization, 2006a). However, in addition to focussing mainly on the risk of failures (Krishnasamy, Khan, & Haddara, 2005), measures are often more concerned with plant productivity (Lofsten, 2000; Bamber, Castka, Sharp, & Motara, 2003) than human factors requirements for reliability.

The current research has demonstrated instead that in addition to the role of design in failures, a quantifiable and significant relationship exists between design and day-to-day reliability. Furthermore, the research demonstrated that group differences in

Design & Maintenance could be quantified based on the aggregated perceptions of maintenance personnel. Other research has recognised the importance of characterising design and maintainability based on judgements of practitioners at the workplace-level (Reiman & Oedewald, 2006a; Reiman, Oedewald, & Rollenhagen, 2005). Reiman and his associates have conducted numerous studies of the maintenance culture in a hazardous industry (i.e. NPP). In their studies, interviews and surveys were used to characterise qualitatively the climate dimensions of a successful maintenance organisation. Their research revealed that an influence of human factors existed, as perceived by maintenance personnel, on the multiple dimensions of the maintenance task. The current findings supported with quantitative data, their concept of the *critical demands* of maintenance, which in this research was related to problem-solving, and the *instrumental demands*, which in this research was related to organisational communication.

9.4.3 Communication

The frequent mention of *Communication* and the frequent contributing role of *Information* and *Procedures* in the interviews in Study 2 supported the association found in the literature between the quality of organisational communication and performance. In Reiman, Oedewald, and Rollenhagen's (2005) examination of maintenance culture in two NPPs, communication climate was one of the variables related to effectiveness in performing the maintenance task. Their results showed communication climate to be significantly correlated with *Job satisfaction, Job motivation,* and *Proficiency*, though with differing results for the two organisations studied. Despite this, neither of the two Study 3 communication variables, *Job-related feedback* or *Information about change,* demonstrated significant group-level differences based on reliability level. An explanation could again be found in the content analysis of the comments. *Organisational communication* was the only variable from Study 3 that emerged in the qualitative analysis as a distinct super-ordinate theme. This super-ordinate theme, *Communication & access to information,* consisted of comments concerning many of the organisational flaws mentioned as contributing to Study 2 failures, namely, flawed organisational communication processes, inadequate procedures, and lack of information (Tables 19-21). Furthermore, the relatively uniform distribution of this super-ordinate theme across different reliability levels (Figure 17) appeared to explain the absence of group differences in the *Organisational communication* variables. The communication climate tended to be characteristic of the entire organisation, whereas reliability was measured at the group-level. This distinction accords with Wiio's (1978) original communication studies with the OCD/2 Audit and its predecessor, the LTT Communication Audit, as well as Aberg's (1986) continuation of Wiio's research. In these studies, communication was discussed as an organisational characteristic, though group-level differences within the organisations studied were also identified. Interestingly, in the Study 3 survey, communication was also confirmed to be an organisational property in the sense that a significant correlation with *Employer* was observed. Lower scores for *Job-related feedback* were significantly associated with the target company's employees relative to contractors. Although this is not a positive result for the company, it does indicate that communication climate is a dimension within the organisation's control, rather than being dependent on the characteristics of a specific workgroup, or the individual traits of maintenance technicians and their supervisors. This contention is supported by triangulating organisational communication findings across the three studies. Insufficient information, inadequate procedures, and poor feedback mechanisms were often mentioned in incidents recorded in the First Priority database, in the interviews, and in the comments of respondents to the survey. In contrast to team-based (group-level) communication effectiveness, which was often argued in the safety literature (Crichton, 2005; Hofmann & Stetzer, 1998) and HRO literature (La Porte, 1996; Roberts & Tadmor, 2002) as being important, the functions arising in the current research were dimensions of communication climate originating instead at the organisational level. The implication is that communication may play a contributing role in failures at the group level, but its role in predicting day-to-day reliability is only differentiated at the organisation level, such as in employer-related differences.

9.4.4 Consideration of other human factors

Company incident reports in Study 1 attributing many failures to *Design & Maintenance* were supported by Studies 2 & 3, but the attribution of failures to violations and human error (i.e., *Violations*, *Detection,* and *Decision-making*) was not supported by the other two studies. Despite the literature (Hobbs & Williamson, 2003; Holmgren, 2005; Reason & Hobbs, 2003) frequently attributing the cause of maintenance failures to violations, the data provided often did not differentiate either the violation-provoking factors (Fergenson, 1971; Holmgren, 2005; Torp & Grøgaard, 2009) or the underlying motivations, as identified in the theoretical discussions of Reason, Parker, and Lawton (1998). Consequently, interviewees in Study 2 were carefully questioned to ensure that violations as a possible contributing factor was fully explored. A common response was that violations of procedures had not been a factor, primarily because procedures were not available for the task. Lack of procedures was a contention supported by comments from Study 3, as in the example, "The main problem retarding my way forward is two-fold, 1. lack of up-to-date procedures…" (Respondent #22). This accords with Taylor's (2007) study of design error in chemical plant accidents. Among the failures he attributed to *Managerial Errors*, ~25% were due to *Inadequate Procedures* and only ~7% were due to *Procedures Not Followed.* A similar ratio of inadequate procedures to violations was identified in Study 2. Violation of rules due to poor availability of procedures is not limited to industrial contexts. In relation to their investigation of an adverse drug event, Iedema, Jorm, Braithwaite, Travaglia, and Lum (2006) argued, "The uptake of formal rules is contingent on the extent to which the rules are woven into the existing fabric of activities" (p. 1207). They found that procedures could only partially specify acceptable actions, after which clinicians needed to adapt systems to the situation, at times in opposition to formal rules. Similarly, the 'procedures' that the First Priority reports in Study 1 claimed should have been followed, often amounted to an idealised concept of how a particular maintenance activity should have proceeded, without regard to what Iedema et al regarded as 'the complexity of everyday situations.' The First Priority incident reports also suffered from the Hindsight Bias discussed by Dekker (2005). He contended that Hindsight Bias is more about modelling what should have occurred in the situation that led to an adverse outcome, than it is about explaining what actually occurred. Similarly, the findings of Studies 1 and 2 indicated that although investigators often concluded that a procedure should have been followed, such a procedure that fully-specified the tasks to be undertaken often did not exist.

Human errors, in the form of *Detection* and *Decision-making* (both sub-categories of *Situation Awareness*) were also often reported in First Priority as contributing factors without reference to situational context. This too is typical of incident investigations that conclude with a finding of human error rather than taking human error as a starting point for further investigation (Dekker, 2006). The current research demonstrated the complexity of analysing each particular failure; company investigations revealed a mean of 2.3 factors per failure, compared to structured, human factors-based interviews that revealed a mean of 9.5 factors per failure. While the intention of the study was not to count errors, which Dekker (2003b; 2007) clearly warned against, the interviews in Study 2 served to reveal the prevalence and interactivity of the specific factors underlying reliability in a complex socio-technical system.

Finally, other factors that the organisational literature tended to regard as important to workgroup performance, such as supervision (O'Dea & Flin, 2001; Wu, Chen, & Li, 2008), training (Kirby, Knapper, Evans, Carty, & Gadula, 2003; McKeon, Cunningham, & Oswaks, 2009; O'Connor & Flin, 2003; Salas, Burke, Bowers, & Wilson, 2001; Salas et al., 2008), and teamwork (Crichton, 2005; Flin, Fletcher, McGeorge, Sutherland, & Patey, 2003; Sexton, Thomas, & Helmreich, 2000) were not frequent contributors to the failures investigated in Studies 1 and 2. Requests for better supervision and more training were mentioned in Study 3 comments aggregated in the super-ordinate theme, *Need for more personnel and better workgroup support systems*. As with communication, this super-ordinate theme was relatively uniformly distributed across reliability levels, indicating it to be an organisation-wide desire for better support for work activities, rather than a direct contributor to failures or poor reliability. As such, the workforce appeared to be following the course of HRO development as described by Ericksen and Dyer (2005), in which personnel recognise the need for greater diligence and responsibility for rectifying situations. Furthermore, the recognition by maintenance personnel of the need for training and better access to information, among other ‘reliability-oriented employee behaviours’ was an expression of a lack of complacency about the challenges that they and the organisation face.

9.4.5 Models

9.4.5.1 Human Malfunction Model

As discussed in the literature review, a framework is required in the assessment of human behaviour in general, and in this particular research, organisational behaviour in relation to reliability outcomes. HFIT (Gordon, Flin, & Mearns, 2005) and the

Human Malfunction model (Rasmussen et al., 1981) upon which it was partly based, has proved to be a useful framework for:

- assigning a formal structure to the human factors contributing to incidents
- quantifying the occurrences of these factors
- deriving logical explanations for the mechanisms involved.

While remaining mindful of Dekker's injunction against 'counting errors' and 'digitising data' (Dekker, 2003b) HFIT taxonomy has provided the means for obtaining a greater understanding of the mechanisms involved in failures.

The current research has shown that it is beneficial for organisations to proceed beyond counting errors and failures to an understanding of the factors supporting day-to-day reliability. Although individual-level traits such as intrinsic motivation, commitment, and job satisfaction, were often explored in the literature and are likely to contribute to reliability, these rarely arose in the current research. The code *Person Factors* was rarely mentioned in the interviews and the *Vigilance* data in Study 3 was not significant. The evidence from Studies 2 and 3 was that group-level and organisational-level factors played a greater role in reliability. These positive group and organisational processes served to oppose the *Drift Into Failure* described in the model initially developed by Rasmussen (1997a) and further refined by Cook and Rasmussen (2005) and Dekker (2005).

9.4.5.2 Drift Into Failure Model

As described in Chapter 2, the Drift Into Failure model postulates that in any organisation there is a safe operating domain, within which the accepted work procedures, team functions, operating limits, and supervisory controls ensure a high probability of reliable operation. Under organisational pressures, such as restricted time and financial resources, organisational 'fine-tuning' (Starbuck & Milliken, 1988), and internal political agendas (Sagan, 1994), drift can occur in day-to-day processes. This drift is accompanied by a decrease in the probability of reliable operation. Eventually, sufficient drift brings these processes into the proximity of safe operating boundaries, essentially the point at which probabilities of failure are higher than the process designers, the organisation's management, or the industry regulators would consider acceptable. In the current context of a petroleum operation, drift in the processes investigated would be predicted to compromise the systems that protect against failures (Urbina, 2010; Øien 2001a; Øien 2001b). From the findings of Studies 2 and 3, at the group level, drift in problem-solving processes implies a reduced ability to manage the *Design & Maintenance* impacts on reliability. In Figure 19, a graphical representation is provided of the theoretical relationship between the factors investigated and organisational outcomes.

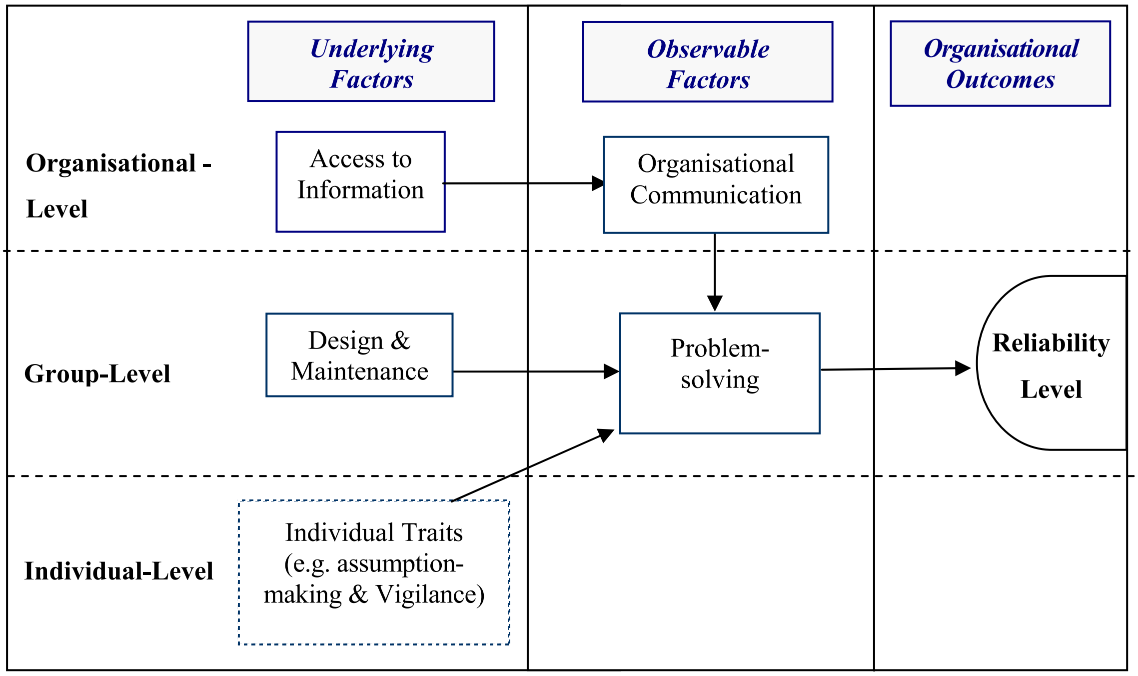

Figure 19. Theoretical relationship between the processes investigated in Studies 2 and 3.

9.4.6 Generalisability of the findings

Application of this research to other organisations is reliant on the generalisability of the findings to other domains, including other companies in the petroleum industry and other industries, and to theoretical human factors research. The factors identified as the most frequent contributors to failure, i.e. assumptions in decision-making and problem-solving, design and maintainability, and organisational communication, were all of sufficient prominence in the literature to be logical candidates for examination in any industrial operation. In addition, these factors were apparent in failures outside of industrial operations, such as the Barings Bank collapse (Choo, 2008). In that failure, poor communication of warning signs and assumptions about the robustness of financial system safeguards permitted the total failure of a financial network. This failure demonstrated the critical role of problem-solving and organisational communication as likely contributors to failure in non-industrial domains as well. However, different organisations are likely to experience different contributing factors in failures, as the significant *Employer*-related differences in *Organisational Communication* scores demonstrated. The current methodology was specifically intended to narrow the range of human factors closely examined to just the most-frequent contributors to failure. It was intended that the methods used would allow any organisation to determine the predominant human factors in its specific context. The selection of the scales relied on the factors found in the preliminary studies, but could be reconfigured based on validated scales for testing organisational, group, and individual characteristics. Reliability ranking of work areas was based on accepted engineering principles, and as such could be derived by comparing work areas in any organisation for which appropriate data was available.

The variables used in the Study 3 survey might not demonstrate the same statistical relationship in another organisation. Each organisation has specific climate characteristics which wholly or in part influence reliability (Bourrier, 1996; Reiman, Oedewald, & Rollenhagen, 2005). It did appear from the literature, however, that modern workplaces commonly experience inadequate communication (Alvarez & Coiera, 2006; Baltes, Dickson, Sherman, Bauer, & LaGanke, 2002; Greenberg et al., 2007; Horwitz et al., 2009) and deficient information systems (Hoffman, 2008), and that industrial designs create the conditions for many failures (Kinnersley & Roelen, 2007; Taylor, 2007) which may be remedied through improved problem-solving skills (Wilpert, 2007) and recognition of the decision-making processes that naturally occur in the workplace (Carvalho, dos Santos, & Vidal, 2005). Therefore, these findings might find immediate application by those industrial organisations attempting to improve reliability via a human factors approach, as well as by the researchers developing a theoretical understanding of the human-machine and human-system interactions which contribute to the evolution of both day-to-day reliability and catastrophic failures.

9.5 Practical Implications for Reliability in Maintenance

9.5.1 Problem-solving

The implications from this research, that problem-solving may moderate the effect of inherently low-reliability technical designs on outcomes, is important to the on-going operation of hazardous facilities. The empirical findings (Figure 18) indicated that the management of complex socio-technical operations would benefit from balancing design considerations at the initial engineering stage, against the problem-solving and informational requirements of the workforce throughout the service life of the plant, if 'acceptable' outcomes are to be attained in terms of the risk of failure and loss of productivity. Much of the design and engineering literature, as discussed in Section 2.6, has attempted to conceptualise the association between design, maintainability, and outcomes as a direct one. The research quoted in Section 2.7 concerning design-related accidents typically recognised that there are contributing factors to these failures, but did not discuss the factors moderating the effects of inherently flawed designs.

From the findings, it appeared that organisations would benefit from identifying and supporting the problem-solving climate that has developed within their workgroups. If the climate is one that favours experienced maintenance personnel utilising a Recognition-Primed Decision-making approach, the organisation will benefit from reducing the frequency of assumptions and increasing the accuracy of the assumptions that are made. This can be promoted by developing expertise and experience among maintenance technicians through active organisational learning. Small failures offer opportunities to learn (Baumard & Starbuck, 2005; Carroll, 1998), provided that there exists a feedback culture based on de-briefings (Lipshitz, 2007), organisation-wide *Lessons Learned* systems (Carnes & Breslau, 2002), or relatively easy access to historical information (Cannon & Edmondson, 2005).

Alternatively, if problem complexity is frequently high and experience is relatively low, such as with a younger workforce, a new operating facility, or a particularly unusual design-related problem, a Recognition-Primed Decision-making approach will engender too many faulty assumptions. A more analytical approach to maintenance trouble-shooting is desirable, as Schaafstal et al (2000) have argued. They found in their investigations that "problems were mainly solved, if at all, by recognition of similarity to a previous problem" (p. 77) and that therefore "it became useful to distinguish between system knowledge and general trouble-shooting strategy" (p.77). Their training of maintenance technicians to formulate problem-solving strategies more analytically was successful, demonstrating that problem-solving climate can be changed to a more organisationally-effective approach if supported by management, as MacDuffie (1997) found in his studies of auto factories. The findings of Studies 2 and 3 showed that management decisions affecting problem-solving climate would benefit from aligning with the demands of inherent design reliability and the characteristics of the maintenance workforce, in order to support the maintenance task and thereby decrease the probability of failure.

9.5.2 Design & Maintenance

The consistency of *Design & Maintenance* across all three studies also demonstrated the need for an integrative approach involving past failure history, relative measures of human factors, and the perceptions of maintenance personnel, all of which have a complimentary role in providing data to support organisational decision-making concerning maintenance (Figure 18). Organisations attempting to fine-tune their socio-technical processes in order to achieve greater efficiencies (Starbuck & Milliken, 1988) would benefit from obtaining equivalent data from each of these sources, as each contributes an additional understanding of the influences of human factors on outcomes. Despite the apparent technical focus of the dimension *Design & Maintenance*, the findings indicated the relationship of *Design & Maintenance* to other human factors, such as *Problem-solving*, which may moderate outcomes from this factor (Figure 19). Companies could benefit from broadening their design considerations to include human factors-based analyses of the factors that influence reliability. As the interview and survey results demonstrated, investigations of specific failures provides direction for closer examination of group-level differences between lower reliability work areas and better-performing work areas. Furthermore, as the comment analysis showed, qualitative data can be used to explain and justify the type and extent of interventions required to reduce the probability of design-related failures.

The influence of *Design & Maintenance* on maintenance activities was both significantly related to reliability, as well as being implicated in the need for acquiring problem-solving skills. Although all operating facilities may experience periods of lower and higher reliability, several of the facilities examined demonstrated consistently lower reliability than seemingly equivalent facilities (Figure 6). Tucker, Edmondson, and Spear (2002) argued that inherent reliability is a characteristic of the workplace; that is, poor design of physical and organisational workplace systems leads to a condition of inherently poor reliability. As Tucker et al. described, nurses and other front-line workers typically ‘work around’ problems, rather than devising second-order solutions to correct the underlying workplace designs that are responsible for the problems.

The origins of low inherent reliability may be due to decision-making in the original design process (Cullen, 2007), in which financial constraints (Aoudia, Belmokhtar, & Zwingelstein, 2008), lack of human factors awareness in design considerations (Bea, 1998), or attempts to fine tune systems with advanced engineering (Starbuck & Milliken, 1988) result in systems in which human factors work against performance. Additionally, low reliability may also be due to historical deterioration of the maintenance function caused by management neglect or policy, as was attributed to the Piper Alpha (Pate-Cornell, 1993) and Bhopal disasters (Pidgeon & O'Leary, 2000). Whether in the original design, or evolving over time, design problems are known to be implicated in approximately half of process plant failures (Kinnersley & Roelen, 2007; Taylor, 2007). The current research demonstrated that in addition to failures, design-related impediments to maintenance activities have a significant influence on day-to-day reliability, and in turn on the problem-solving skills required to achieve acceptable performance according to organisational requirements. As such, design decisions have implications for the ability of the plant to be maintained throughout its operating life.

The importance of the concept of maintainability has been accepted in engineering theory (Tjiparuro & Thompson, 2004) along with consideration of the practical requirements of maintainability (International Standards Organization, 2006a; Mason, 1990; Wani & Gandhi, 1999). The means of designing facilities to automate control and improve the interfacing of humans to machines has similarly received attention (Jamieson & Vicente, 2005). However, the evidence from the current research was that *Design & Maintenance* was still a major contributor to human factors-related failures, and that, when asked, maintenance personnel were often aware of the specific *Design & Maintenance* impediments in their work areas. At the same time, comments concerning *Design & Maintenance* were virtually absent from survey responses, other than noting the lack of spares. The implication was that although plant design influenced reliability level, and maintenance personnel were aware of these influences, maintenance personnel did not consider plant design their concern. Apparently, the design of a plant was taken as a given, and maintenance personnel tended to 'work with what they had'. This view accorded with Cooke's (2002) description of maintenance technicians in manufacturing as generally having no input into plant design and equipment selection, and little involvement at the installation and commissioning stages. Yet, they are still required to ensure that equipment functions reliably, and are often called upon to modify the original design.

Despite the focus of maintenance personnel on human factors rather than design in their comments, it can be argued from the evidence of Study 1 that incident investigators were still not yet able to recognise the human factors associated with failures involving *Design & Maintenance.* This may not be uncommon among incident investigators (Reinach & Viale, 2006) or managers striving to prevent these failures (Crichton, 2005; O'Dea & Flin, 2001) due to their lack of human factors expertise. However, until organisations develop this ability to analyse the human factors contributing to incidents and better utilise the knowledge of maintenance personnel to correct design flaws, advances in reliability outcomes will be limited by the problem-solving abilities of maintenance personnel.

9.5.3 Communication

As mentioned, an important requirement of successful use of both Recognition-Primed Decision-making and analytical problem-solving relies on easily accessible task-related information. This applies to information from colleagues as well as from electronic information systems. The findings in Study 2, and the qualitative data from Study 3 relating to communication (Figure 18), supported the important role of organisational communication and access to information in preventing failures and providing the resources that maintenance personnel perceive as needed to ensure reliability. Furthermore, the results demonstrated that level considerations are critical in assessing organisational communication. The evidence from Study 3 (Figure 19) indicated that organisational communication, as the name implies, is an organisation-level dimension, and that therefore addressing deficiencies lies within a company's control. The significant correlation between *Job-related feedback* and *Employer* (Figure 15) further supported this contention, showing that workers in the same workplace may experience communication climate differently if they are employed by different companies. The implication from the current research is that communication and access to information needs to be addressed by the organisation as a whole, as solutions do not appear to develop at the group-level. This conclusion particularly pertains to the concerns about impediments to obtaining information from electronic sources, supporting Baltes et al's (2002) evidence that the quality of group decision-making decreases with the use of computer-mediated communication. Statements from maintenance personnel in both Study 2 interviews and Study 3 comments frequently expressed dissatisfaction with information mediated by electronic information management systems, such as the SAP database. Thus, although the role of communication in supporting problem-solving was not demonstrated in group-level processes tested in Study 3, it clearly played a supporting role in facilitating processes at the organisation-level, and therefore its impact on group-level outcomes still warrants investigation.

9.6 Directions for Future Research

9.6.1 Method development

Further refinement of the data collection methods used in the research would be beneficial in addressing the methodological limitations discussed previously (Section 7.4.6 and 9.3.2). The current research approach could be extended in other directions. This might include a longitudinal study of the effects of interventions designed to improve the areas of organisational weakness identified in the research, namely problem-solving methods, organisational communication, and the ease of access to information. An intervention study would have a three fold purpose:

1) A pre-test replication of the survey would provide an indication of the stability of the measures over time.

2) A post-test survey might demonstrate the relationship of the problem-solving and organisational communication variables to changing reliability levels.

3) A post-test survey with control groups could be used to determine the sensitivity of the measures to the effects of interventions.

9.6.2 Additional research directions

The current research demonstrated the importance of relating group-level variables to group-level outcome differences. However the impact of human factors variables at the individual and organisational level on group-level processes was not specifically investigated. From the literature reviewed (Cassignol-Bertrand, Baldet, Louche, & Papet, 2006; Martin, 2004; Meyer, Becker, & Vandenberghe, 2004), the individual-level traits of job satisfaction, commitment, and intrinsic motivation are likely to have an influence on performance. The richness of the data provided in the survey comments demonstrated that the respondents had a high level of commitment to achieving positive outcomes and a motivation to do their work efficiently. However, this may not apply to the other maintenance staff (N=77) who completed the questionnaire without commenting, or the 58% of maintenance personnel who did not return a completed questionnaire. The CULTURE questionnaire, developed by Reiman and Oedewald (2004), provides a promising methodology for investigating the role of these individual differences in maintenance outcomes. Controlling for the influence of individual traits may provide a more complete explanation of the role of problem-solving and vigilance in managing maintenance problems, as well as the attitudes to differences encountered in design and maintenance.

Similarly, at the organisation-level, the literature indicates the important role of organisational learning in correcting faults in the design of workplaces (Carroll, 1998; Marsick & Watkins, 2003), as well as in providing a feedback mechanism whereby information learned through problem-solving is incorporated into organisational understanding and processes (Barkai & Samuel, 2005; Carnes & Breslau, 2002). In Study 1, it was observed that the *Lessons Learned* section of the First Priority form was rarely completed. At the same time, in Study 2, it was often mentioned that learnings from failures would not be fed back into workplace systems and that errors were likely to be repeated. Although organisational learning was not tested *per se* in Study 3, a number of comments supported the findings from Studies 1 and 2, namely that learnings were often not communicated, and therefore the probability of future failures was not reduced. The extent of organisational learning may be an important covariate in both the scores from *Problem-Solving* and *Communication*. Measuring and controlling for perceptions of organisational learning as a separate variable may clarify the way in which problem-solving and communication influence reliability outcomes.

Finally, the influence of procedural violations on reliability outcomes was frequently suggested in the maintenance literature (Hobbs & Williamson, 2003; Holmgren, 2005; Pyy, 2001). Although Study 1 found that failures were frequently attributed to violations (Figure 3), a similar relationship was not identified in Studies 2 and 3. This may be due to the nature of data collection in the latter studies, which was primarily based on self-reports. An alternative (i.e., more 'objective') method of assessing group-level differences in the prevalence of violations, such as behavioural observations (Glendon & Litherland, 2001), may reveal a stronger relationship to reliability level than was identified in this research.

9.7 General Conclusions

Each technical failure reinforces the perceived potential for hazardous operations to fail catastrophically and the need for better control of complex technologies, such as those in petroleum operations (Urbina, 2010). Industrial workers in general and maintenance personnel in particular are responsible for control of these technologies, and for maintaining their reliability. At the same time, the managers of these technologies have agendas which include reliability, but, as Schein (1996) agued in his comparison of operator, engineering, and executive cultures, may not focus on the needs and opinions of the workers responsible for it. Consequently, as Starbuck and Milliken (1988) contended, organisations are inclined to 'fine-tune' advanced systems by increasing output and reducing input resources to the point where probability of failure drifts to an unacceptable level. Despite this influence of the decisions made by organisations, the people working closest to the technology are the first to be blamed for its failure. Thus, 'pilot error', 'maintenance failure', and 'violation of established procedures' are among the first labels attached to many failures and accidents (Reason & Hobbs, 2003).

Although they have a responsibility for outcomes, maintenance personnel are rarely recognised for their awareness of the condition of equipment and weaknesses of the systems with which they interact on a routine basis. In Cooke's (2002) analysis of the role of maintenance workers in five British firms undergoing change, she identified that:

> "Maintenance workers have a more important role to play in technological change than is commonly assumed by their managers and by writers on maintenance work. Instead of being passive recipients of, or a source of resistance to, technological change, they can, and are willing to, facilitate and initiate technological change in their organizations." (p.963)

The findings of the current research support this conclusion, namely that firms would benefit from utilising the perceptions and situated insights of maintenance workers. Maintenance personnel were found to have the domain knowledge, situation awareness, motivation, and interactivity with the technologies that could provide the data that organisations require to deal with the reliability flaws that are commonly inherent in equipment and plant designs. Furthermore, by equipping maintenance technicians in particular with more effective problem-solving strategies and improved access to task-related information, they may be better-equipped to counter the effects of any inherent reliability flaws in plant designs. The feedback involved in analysing and correcting both immediate and underlying problems, and facilitating organisational communication, represent an important process of second-order organisational learning. Tucker and Edmondson (2003) found that front-line workers, such as nurses are able to solve first-order problems, but they need the support of management to redesign work systems in order to prevent future recurrences. As plant and systems become more complex and tightly coupled, maintenance personnel will need to become better equipped to analyse the problems inherent in the equipment they manage, and have a role in improving the overall effectiveness of the technology and equipment they control. The starting point of this process is better information and understanding concerning the human factors in workplace functions.

The current research has attempted to demonstrate that the perceptions of maintenance personnel were the best place to begin acquiring this understanding of human factors in the workplace. Based on interviewees' descriptions in Study 2, petroleum companies will benefit from addressing instances of inadequate design and limited equipment maintainability, if they wish to reduce the incidence of failures. At the same time, steps could be taken to become a 'higher reliability organisation' by ensuring adequate organisational communication, and greater information flow between participants in the maintenance process. Where reliability has been identified as inherently low, petroleum companies would also benefit from enhancing the problem-solving skills of maintenance personnel. More emphasis is required on developing broader strategies for solving maintenance problems across a wide range of equipment types, rather than allowing organisational pressures to impose an exclusively Recognition-Primed Decision-making approach. Finally, instead of focusing on human error and procedural violations, a more thorough examination of underlying organisational weaknesses will assist in the organisational development needed to counter threats to process safety and continuity of petroleum production.

References

Aberg, L. (1986). *Information-seeking structures in work organizations: Structural parameters, measurement techniques and empirical results for 18 Finnish work organizations* (Viestintatutkimuksen Seuran Julkaisusarja No.10). Helsinki: Dept. of Commerce, U. of Helsinki.

Ajzen, I. (1991). The theory of planned behavior. *Organizational Behavior and Human Decision Processes, 50*(2), 179-211.

Allen, P., & Bennett, L. (2008). *SPSS for the Health and Behavioural Sciences* (1st ed.). Melbourne: Thomson Nelson Australia.

Alvarez, G., & Coiera, E. (2006). Interdisciplinary communication: An uncharted source of medical error? *Journal of Critical Care, 21*(3), 236-242.

Antelman, G. (1997). *Elementary Bayesian Statistics*. Cheltenham, UK: Edward Elgar Publishing.

Antonovsky, A. (2006). Compound Failure Modes. *Materials Forum, 30*, 159-163.

Aoudia, M., Belmokhtar, O., & Zwingelstein, G. (2008). Economic impact of maintenance management ineffectiveness of an oil and gas company. *Journal of Quality in Maintenance Engineering, 14*(3), 237.

Argyris, C., & Schon, D. A. (1996). *Organizational learning II : theory, method and practice*. Reading, Mass.: Addison-Wesley.

Axtell, C., Wall, T., Stride, C., Pepper, K., & et al. (2002). Familiarity breeds content: The impact of exposure to change on employee openness and well-being. *Journal of Occupational and Organizational Psychology, 75*, 217.

Baker, G. (2002). The effects of synchronous collaborative technologies on decision making: A study of virtual teams. *Information Resources Management Journal, 15*(4), 79.

Baltes, B. B., Dickson, M. W., Sherman, M. P., Bauer, C. C., & LaGanke, J. S. (2002). Computer-Mediated Communication and Group Decision Making: A Meta-Analysis. *Organizational Behavior and Human Decision Processes, 87*(1), 156-179.

Bamber, C. J., Castka, P., Sharp, J. M., & Motara, Y. (2003). Cross-functional team working for overall equipment effectiveness (OEE). *Journal of Quality in Maintenance Engineering, 9*(3), 223.

Bandura, A., & Locke, E. A. (2003). Negative self-efficacy and goals revisited. *Journal of Applied Psychology, 88*, 87-99.

Barkai, I., & Samuel, Y. (2005). *The Use of Organizational Learning Mechanisms: Environmental, Managerial and Cultural Correlates.* Paper presented at the Academy of Management Proceedings.

Barling, J., Loughlin, C., & Kelloway, E. K. (2002). Development and test of a model linking safety-specific transformational leadership and occupational safety. *Journal of Applied Psychology,, 87*(3), 488-496.

Baumard, P., & Starbuck, W. H. (2005). Learning from failures: Why it May Not Happen. *Long Range Planning, 38*(3), 281-298.

Bea, R. G. (1998). Human and organization factors: engineering operating safety into offshore structures. *Reliability Engineering & System Safety, 61*(1-2), 109-126.

Bourrier, M. (1996). Organizing maintenance work at two American nuclear power plants. *Journal of Contingencies & Crisis Management, 4*(2), 104.

Bourrier, M. (2005). The contribution of organizational design to safety. *European Management Journal, 23*(1), 98-104.

Brehmer, B. (1993). Cognitive aspects of safety. In B. Wilpert & T. Qvale (Eds.), *Reliability and safety in hazardous work systems*. Hillsdale, USA: Lawrence Erlbaum Associates.

Brief, A. P., & Weiss, H. M. (2002). Organizational behavior: Affect in the workplace. *Annual Review of Psychology, 53*, 279-307.

Brooke, J. (1996) SUS: a "quick and dirty" usability scale. In P. W. Jordan, B. Thomas, B. A. Weerdmeester & A. L. McClelland (eds.) Usability Evaluation in Industry. London: Taylor and Francis.

Cacciabue, P. C., & Cojazzi, G. A. (1994). A human factor methodology for safety assessment based on the DYLAM approach. *Reliability Engineering & System Safety, 45*, 127-138.

Cacciabue, P. C. (2000). Human factors impact on risk analysis of complex systems. *Journal of Hazardous Materials, 71*(1-3), 101-116.

Cannon, M. D., & Edmondson, A. C. (2005). Failing to learn and learning to fail (intelligently): How great organizations put failure to work to innovate and improve. *Long Range Planning, 38*(3), 299-319.

Carnes, W. E., & Breslau, B. (2002). *Lessons learned: improving performance through organizational learning.* Paper presented at the IEEE 7th Conference on Human Factors and Power Plants, Scottsdale, Arizona.

Carr, J. Z., Schmidt, A., M. , Ford, J. K., & DeShon, R., P. (2003). Climate perceptions matter: A meta-analytic path analysis relating molar climate, cognitive and affective states, and individual level work outcomes. *Journal of Applied Psychology, 88*(4), 605.

Carroll, J. S. (1998). Organizational learning activities in high-hazard industries: The logics underlying self-analysis. *Journal of Management Studies, 35*(6), 699.

Carvalho, P. V. R., dos Santos, I. L., & Vidal, M. C. R. (2005). Nuclear power plant shift supervisor's decision making during micro-incidents. *International Journal of Industrial Ergonomics, 35*(7), 619-644.

Cassignol-Bertrand, F., Baldet, S., Louche, C., & Papet, J. (2006). Norme de motivation intrinseque et utilite sociale : recherches dans le champ organisationnel. *Psychologie du Travail et des Organisations, 12*(4), 339-349.

Chalton, S. G., & O'Brien, T. G. (2002). *Handbook of Human Factors Testing and Evaluation* (2nd ed.). Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Cheng, Z., Jia, X., Gao, P., Wu, S., & Wang, J. (2008). A framework for intelligent reliability centered maintenance analysis. *Reliability Engineering and System Safety, 93*(6), 806-814.

Choi, J. N., Price, R. H., & Vinokur, A. D. (2003). Self-efficacy changes in groups: effects of diversity, leadership, and group climate. *Journal of Organizational Behavior, 24*(4), 357.

Choo, C. W. (2008). Organizational disasters: why they happen and how they may be prevented. *Management Decision, 46*(1), 32-45.

Collier, J. D. (2004). Human factors in maintenance -- Another reminder. *Overhaul & Maintenance, 10*(7), 27.

Comerford, N. (2009a). (pp. Personal Communication).

Comerford, N. (2009b). *Operational Reliability Improvement (ORIP) Standard* (No. W6504SG3836292 Rev2). Perth: Woodside Energy Limited.

Cooke, F. L. (2002). The important role of the maintenance workforce in technological change: A much neglected aspect. *Human Relations, 55*(8), 963-988.

Cooke, F. L. (2003). Plant maintenance strategy: Evidence from four British manufacturing firms. *Journal of Quality in Maintenance Engineering, 9*(3), 239.

Cooke, N. J., Salas, E., Cannon-Bowers, J. A., & Stout, R. J. (2000). Measuring team knowledge. *Human Factors, 42*(1), 151.

Cox, S. J., & Cheyne, A. J. T. (2000). Assessing safety culture in offshore environments. *Safety Science, 34*(1-3), 111-129.

Crichton, M. (2005). Attitudes to teamwork, leadership, and stress in oil industry drilling teams. *Safety Science, 43*(9), 679-696.

Cullen, L. (2007). Human factors integration- Bridging the gap between system designers and end-users: A case study. *Safety Science, 45*, 621-629.

Culvenor, J. (2003). Comparison of team and individual judgements of solutions to safety problems. *Safety Science, 41*(6), 543-556.

De Groote, P. (1995). Maintenance performance analysis: a practical approach. *Journal of Quality in Maintenance Engineering, 1*(2), 4.

Dekker, S. (2003a). Failure to adapt or adaptations that fail: contrasting models on procedures and safety. *Applied Ergonomics, 34*(3), 233-238.

Dekker, S. (2003b). Illusions of explanation: A critical essay on error classification. *International Journal of Aviation Psychology, 13*(2), 95-106.

Dekker, S. (2005). *Ten Questions About Human Error: A New View of Human Factors and System Safety (Human Factors in Transportation)* Mahwah: Lawrence Erlbaum Associates, Inc.

Dekker, S. (2006). *The Field Guide to Understanding Human Error*. Aldershot: Ashgate Publishing Ltd.

Dekker, S. (2007). Doctors are more dangerous than gun owners: A rejoinder to error counting. *Human Factors, 49*(2), 177.

Dhillon, B. S. (2002). *Engineering Maintenance- A Modern Approach*. Boca Raton: CRC Press.

Dorner, D. (1987). On the difficulty people have in dealing with complexity. In J. Rasmussen, K. Duncan & J. Leplat (Eds.), *New Technology and Human Error*. New York: John Wiley & Sons.

Downs, C. (2004). Organizational Communication Development Audit Questionnaire. In R. Rubin, P. Palmgreen & H. Sypher (Eds.), *Communication Research Measures* (pp. 247-253). Mahwah, New Jersey: Lawrence Erlbaum Associates.

Downs, C., & Hazen, M. D. (1977). A factor analytical study of communication satisfaction. *Journal of Business Communication, 14*(3), 63-73.

Dymock, D., & McCarthy, C. (2006). Towards a learning organization? Employee perceptions. *The Learning Organization, 13*(5), 525-536.

Edmondson, A. C. (1996). Learning from mistakes is easier said than done: Group and organizational influences on the detection and correction of human error. *The Journal of Applied Behavioral Science, 32*(1), 5.

Edmondson, A. C. (1999). Psychological safety and learning behavior in work teams. *Administrative Science Quarterly, 44*(2), 350-383.

Edwards, B. D., Bell, S., T. , Arthur, W., & Decuir, A., D. . (2008). Relationships between facets of job satisfaction and task and contextual performance. *Applied Psychology, 57*(3), 441-465.

Einstein, A. (1926). *Wikiquote: Albert Einstein.* Retrieved 22 October, 2009 from http://en.wikiquote.org/wiki/Albert_Einstein#Science_and_Religion_.281941.29

Ericksen, J., & Dyer, L. (2005). Toward a strategic human resource management model of high reliability organization performance. *Int. J. of Human Resource Management, 16*(6).

Eti, M. C., Ogaji, S. O. T., & Probert, S. D. (2006). Impact of corporate culture on plant maintenance in the Nigerian electric-power industry. *Applied Energy, 83*(4), 299-310.

Fergenson, E. P. (1971). The relationship between information processing and driving accident and violation record. *Human Factors, 13*, 173-176.

Flin, R., Fletcher, G., McGeorge, P., Sutherland, A., & Patey, R. (2003). Anaesthetists' attitudes to teamwork and safety. *Anaesthesia, 58*(3), 233-242.

Flin, R., Mearns, K., O'Connor, P., & Bryden, R. (2000). Measuring safety climate: identifying the common features. *Safety Science, 34*(1-3), 177-192.

Flin, R., O'Connor, P., Mearns, K., & Gordon, R. (1999). *Crew resource management for offshore production and maintenance.* Paper presented at the 1999 Offshore Europe Conference, Aberdeen, Scotland.

Geller, E. S., & Douglas, M. W. (2005). People-Based Safety: Exploring the role of personality in injury prevention. *Professional Safety, 50*(12), 28.

Gertman, D. I., Hallbert, B. P., Blackman, H. S., Parrish, M. W., Trager, E. A., Persensky, J. J., et al. (2002). *Human performance contribution to risk in* *nuclear power operating events.* Paper presented at the IEEE 7th Conference on Human Factors and Power Plants, Scottsdale, Arizona.

Gherardi, S., Nicolini, D., & Odella, F. (1998). Toward a social understanding of how people learn in organizations. *Management Learning, 29*(3), 273.

Glendon, A. I., Clarke, S. G., & McKenna, E. F. (2006). *Human Safety and Risk Management* (Second Edition ed.). Boca Raton, USA: Taylor & Francis Group.

Glendon, A. I., G., & Litherland, D. K. (2001). Safety climate factors, group differences and safety behaviour in road construction. *Safety Science, 39*(3), 157-188.

Gordon, R. (1998). The contribution of human factors to accidents in the offshore oil industry. *Reliability Engineering & System Safety, 61*(1-2), 95-108.

Gordon, R. (2001). Human Factors Investigation System HFIT: University of Aberdeen, Industrial Psychology Group.

Gordon, R., Flin, R., & Mearns, K. (2005). Designing and evaluating a human factors investigation tool (HFIT) for accident analysis. *Safety Science, 43*(3), 147-171.

Gordon, R., Mearns, K., & Flin, R. (2000). *The development and evaluation of a human factors accident and near miss reporting tool (HFIT) for the off-shore oil industry.* (Vol. 2). London: HSE Books.

Greenbaum, H. H., Clampitt, P., & Willihnganz, S. (1988). Organizational communication: An examination of four instruments. *Management Communication Quarterly, 2*(2), 245-282.

Greenberg, C. C., Regenbogen, S. E., Studdert, D. M., Lipsitz, S. R., Rogers, S. O., Zinner, M. J., et al. (2007). Patterns of Communication Breakdowns Resulting in Injury to Surgical Patients. *Journal of the American College of Surgeons, 204*(4), 533-540.

Heimann, L. (2005). Repeated failures in the management of high risk technologies. *European Management Journal, 23*(1), 105-117.

Hiller, N. J., Day, D. V., & Vance, R. J. (2006). Collective enactment of leadership roles and team effectiveness: A field study. *The Leadership Quarterly, 17*(4), 387-397.

Hobbs, A., & Williamson, A. (2002). Skills, rules and knowledge in aircraft maintenance: errors in context. *Ergonomics, 45*(4), 290-308.

Hobbs, A., & Williamson, A. (2003). Associations between errors and contributing factors in aircraft maintenance. *Human Factors, 45*(2), 186.

Hobbs, A. N. (2000). *Human Errors in Context: A Study of Unsafe Acts in Aircraft Maintenance.* PhD. Thesis, U. of NSW, Sydney.

Hodgkinson, G. P., & Healey, M. P. (2008). Cognition in Organizations. *Annual Review of Psychology, 59*(1), 387-417.

Hoffman, R. (2008). Human Factors Contributions to Knowledge Elicitation. *Human Factors, 50*(3), 481.

Hofmann, D. A., & Stetzer, A. (1998). The role of safety climate and communication in accident interpretation: Implications for learning from negative events. *Academy of Management Journal, 41*(6), 644-657.

Hokstad, P., Øien, K., & Reinertsen, R. (1998). Recommendations on the use of expert judgment in safety and reliability engineering studies. Two offshore case studies. *Reliability Engineering & System Safety, 61*(1-2), 65-76.

Hollnagel, E. (2002). *Understanding accidents-from root causes to performance variability.* Paper presented at the IEEE 7th Human Factors Meeting, Scottsdale, Arizona.

Hollnagel, E. (2006). Resilience:The challenge of the Unstable. In E. Hollnagel, D. D. Woods & N. Leveson (Eds.), *Resilence Engineering* (First ed., pp. 16-17). Aldershot: Ashgate Publishing Ltd.

Holmgren, M. (2005). Maintenance-related losses at the Swedish Rail. *Journal of Quality in Maintenance Engineering, 11*(1), 5.

Horwitz, L. I., Meredith, T., Schuur, J. D., Shah, N. R., Kulkarni, R. G., & Jenq, G. Y. (2009). Dropping the baton: A qualitative analysis of failures during the transition from emergency department to inpatient care. *Annals of Emergency Medicine, 53*(6), 701-710.

Howell, D. C. (2004). *Fundamental Statistics for the Behavioral Sciences* (Fifth ed.). Belmont, California: Brooks/Cole-Thomson Learning.

Hudson, P. (2007). Implementing a safety culture in a major multi-national. *Safety Science, 45*(6), 697-722.

Hudson, P., Parker, D., Lawton, R., & van der Graaf, G. C. (2002). *Managing non-compliance: moving from theory to practice.* Paper presented at the 6th SPE International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Kuala Lumpur, Malaysia.

Hughes, E. C. (1951). Mistakes at work. *The Canadian Journal of Economics and Political Science, 17*(3), 320-327.

Iedema, R. A. M., Jorm, C., Braithwaite, J., Travaglia, J., & Lum, M. (2006). A root cause analysis of clinical error: Confronting the disjunction between formal rules and situated clinical activity. *Social Science & Medicine, 63*(5), 1201-1212.

International Standards Organization. (1998). Ergonomic requirements for office work with visual display terminals (VDTs) — Part 11: Guidance on usability (First ed., Vol. ISO 9241-11:1998(E)): International Organization for Standardization.

International Standards Organization. (2006a). Maintainability of Equipment , Part 2: Maintainability requirements and studies during the design and development phase (Second ed., Vol. Intl Std 60706-Part 2, pp. 15-19): International Organization for Standardization.

International Standards Organization. (2006b). Petroleum, petrochemical and natural gas industries-Collection and exchange of reliability and maintenance data for equipment (Second ed., Vol. ISO 14224:2006(E)): International Organization for Standardization.

James, W. (1890). *The Principles of Psychology*. New York: H.Holt and Company.

Jamieson, G. A., & Vicente, K. J. (2005). Designing Effective Human-Automation-Plant Interfaces: A Control-Theoretic Perspective. *Human Factors, 47*(1), 12.

Janis, I., & Mann, L. (1977). *Decision Making: A Psychological Analysis of Conflict, Choice and Commitment*. New York: The Free Press.

Jones, B. M., & Cox, S. J. (2003). *LearnSafe-Learning Organisations for Nuclear Safety* Paper presented at the Organisational Learning and Knowledge 5th International Conference, Lancaster, UK.

Jones, S., Kirchsteiger, C., & Bjerke, W. (1999). The importance of near miss reporting to further improve safety performance. *Journal of Loss Prevention in the Process Industries, 12*(1), 59-67.

Kadak, A. C., & Matsuo, T. (2007). The nuclear industry's transition to risk-informed regulation and operation in the United States. *Reliability Engineering & System Safety, 92*(5), 609-618.

Kariuki, S. G., & Löwe, K. (2007). Integrating human factors into process hazard analysis. *Reliability Engineering & System Safety, 92*(12), 1764-1773.

Kelloway, E. K., Mullen, J., & Francis, L. (2006). Divergent effects of transformational and passive leadership on employee safety. *Journal of Occupational Health Psychology, 11*(1), 76-86.

Kerr, N. L., & Tindale, R. S. (2004). Group performance and decision making. *Annual Review of Psychology, 55*(1), 623-655.

Kinnersley, S., & Roelen, A. (2007). Contribution of design to accidents. *Safety Science, 45*(1-2), 31.

Kirby, J. R., Knapper, C. K., Evans, C. J., Carty, A. E., & Gadula, C. (2003). Approaches to learning at work and workplace climate. *International Journal of Training & Development, 7*(1), 31-52.

Kirwan, B. (1994). *A Guide to Practical Human Reliability Assessment* (1st ed.). London: Taylor and Francis.

Khan, F. I., Amyotte, P. R., & DiMattia, D. G. (2006). HEPI: A new tool for human error probability calculation for offshore operation. *Safety Science, 44*(4), 313-334.

Klein, G. (1997). The current status of the naturalistic decision-making framework. In R. Flin, E. Salas, M. Strub & L. Martin (Eds.), *Decision-making under stress: emerging themes and applications* (pp. 11-28). Aldershot: Ashgate.

Klein, R. L., Bigley, G. A., & Roberts, K. H. (1995). Organizational culture in high reliability organizations: An extension. *Human Relations, 48*(7), 771.

Kontogiannis, T. (1999). User strategies in recovering from errors in man-machine systems. *Safety Science, 32*(1), 49-68.

Kozlowski, S. W., & Doherty, M. L. (1989). Integration of climate and leadership: Examination of a neglected issue. *Journal of Applied Psychology 74*(4), 546-553.

Krishnasamy, L., Khan, F., & Haddara, M. (2005). Development of a risk-based maintenance (RBM) strategy for a power-generating plant. *Journal of Loss Prevention in the Process Industries, 18*(2), 69-81.

La Porte, T. R. (1996). High Reliability Organizations: Unlikely, demanding and at risk. *Journal of Contingencies & Crisis Management, 4*(2), 60.

Latham, G. P., & Pinder, C. C. (2005). Work motivation theory and research at the dawn of the Twenty-first Century. *Annual Review of Psychology, 56*(1), 485-516.

Latorella, K. A., & Prabhu, P. V. (2000). A review of human error in aviation maintenance and inspection. *International Journal of Industrial Ergonomics, 26*(2), 133-161.

Lawton, R. (1998). Not working to rule: Understanding procedural violations at work. *Safety Science, 28*(2), 77-95.

Lawton, R., Parker, D., Manstead, A., & Stradling, S. (1997). The role of affect in predicting social behaviors: the case of road traffic violations. *Journal of Applied Social Psychology, 27*(14), 1258-1276.

Lewis, E. E. (1996). *Introduction to Reliability Engineering* (2nd Ed. ed.). New York: John Wiley and Sons.

Lipshitz, R. (2007). *Demystifying organizational learning*. Thousand Oaks, California: Sage Publications.

Lipshitz, R., Klein, G., Orasanu, J., & Salas, E. (2001). Taking stock of naturalistic decision making. *Journal of Behavioral Decision Making, 14*(5), 331.

Lofsten, H. (2000). Measuring maintenance performance - in search for a maintenance productivity index. *International Journal of Production Economics, 63*(1), 47-58.

Lorenzo, D. K., Vanden Heuvel, L. N., & Rooney, J. J. (2006). Improving safety by improving human performance. *Chemical Engineering Progress, 102*(8), 28-33.

Louche, C., & Lanneau, C. (2004). Effets a long terme de l'engagement dans une organisation industrielle. *Psychologie du Travail et des Organisations, 10*(2), 189-203.

Lyons, E., & Coyle, A. (2007). *Analysing Qualitative Data in Psychology*. London: Sage Publications Ltd.

MacDuffie, J. P. (1997). The road to `root cause': Shop-floor problem-solving at three auto assembly plants. *Management Science, 43*(4), 479.

Mann, L., Burnett, P., Radford, M., & Ford, S. (1997). The Melbourne Decision Making Questionnaire. *Journal of Behavioral Decision Making, 10*(1), 1-19.

Marsick, V. J., & Watkins, K. E. (2003). Demonstrating the value of an organization's learning culture: The dimensions of the learning organization questionnaire. *Advances in Developing Human Resources, 5*(2), 132.

Martin, A. J. (2004). The Role of Positive Psychology in Enhancing Satisfaction, Motivation, and Productivity in the Workplace. *Journal of Organizational Behavior Management, 24*(1,2), 113.

Marx, D. (1998). Learning from our mistakes: a review of maintenance error investigation and analysis systems. *US Federal Aviation Administration, Office of Aviation Medicine*.

Mason, S. (1990). Improving plant and machinery maintainability. *Applied Ergonomics, 21*, 15-24.

Mathieu, J. E., Goodwin, G. F., Heffner, T. S., Salas, E., & Cannon-Bowers, J. A. (2000). The influence of shared mental models on team process and performance. *Journal of Applied Psychology, 85*(2), 273-283.

McDonald, N., Corrigan, S., Daly, C., & Cromie, S. (2000). Safety management systems and safety culture in aircraft maintenance organisations. *Safety Science, 34*(1-3), 151-176.

McKeon, L. M., Cunningham, P. D., & Oswaks, J. S. D. (2009). Improving Patient Safety: Patient-Focused, High-Reliability Team Training. *Journal of Nursing Care Quality, 24*(1), 76-82.

Mearns, K., Whitaker, S. M., & Flin, R. (2003). Safety climate, safety management practice and safety performance in offshore environments. *Safety Science, 41*(8), 641-680.

Meyer, J. P., Becker, T. E., & Vandenberghe, C. (2004). Employee Commitment and Motivation: A Conceptual Analysis and Integrative Model. *Journal of Applied Psychology, 89*(6), 991-1007.

Morgeson, F. P., & Humphrey, S. E. (2006). The Work Design Questionnaire (WDQ): Developing and Validating a Comprehensive Measure for Assessing Job Design and the Nature of Work. *Journal of Applied Psychology, 91*(6), 1321-1339.

Moubray, J. (1997). *Reliability-centered maintenance* (2nd ed.). Oxford: Butterworth Heinemann.

Muchinsky, P. M. (2003). *Psychology Applied to Work* (Seventh ed.). Belmont, California: Wadsworth Thomson Learning.

Munipov, V. M. (1992). Chernobyl operators: criminals or victims? *Applied Ergonomics, 23*(5), 337-342.

Muse, L., A. , & Stamper, C., L. . (2007). Perceived Organizational Support: Evidence for a Mediated Association with Work Performance. *Journal of Managerial Issues, 19*(4), 517.

O'Connor, P., & Flin, R. (2003). Crew Resource Management training for offshore oil production teams. *Safety Science, 41*(7), 591-609.

O'Dea, A., & Flin, R. (2001). Site managers and safety leadership in the offshore oil and gas industry. *Safety Science, 37*(1), 39-57.

O'Leary, M. (2002). The British Airways human factors reporting programme. *Reliability Engineering & System Safety, 75*(2), 245-255.

O'Reilly, C. A., & Roberts, K. H. (1977). Task Group Structure, Communication, and Effectiveness in Three Organizations. *Journal of Applied Psychology, 62*(6), 674.

Oedewald, P., & Reiman, T. (2002). *Maintenance core task and maintenance culture.* Paper presented at the IEEE 7th Conference on Human Factors and Power Plants, Scottsdale, Arizona

Oedewald, P., & Reiman, T. (2003). Core task modelling in cultural assessment: a case study in nuclear power plant maintenance. *Cognition, Technology & Work, V5*(4), 283-293.

Øien, K. (1998). Improved quality of input data for maintenance optimization using expert judgment. *Reliability Engineering & System Safety, 60*(2), 93-101.

Øien, K. (2001a). A framework for the establishment of organizational risk indicators. *Reliability Engineering & System Safety, 74*(2), 147-167.

Øien, K. (2001b). Risk indicators as a tool for risk control. *Reliability Engineering & System Safety, 74*(2), 129-145.

Parker, C., Baltes, B., Young, S., Huff, J., Altmann, R., Lacost, H., & Roberts, J. (2003). Relationships between psychological climate perceptions and work outcomes: a meta-analytic review. *Journal of Organizational Behavior 24*(4), 389.

Pate-Cornell, M. E. (1993). Learning from the Piper Alpha Accident: A Postmortem Analysis of Technical and Organizational Factors. *Risk Analysis, 13*(2), 215-232.

Patton, M. Q. (2002). *Qualitative Research and Evaluative Methods* (Trans. Third Edition ed.). Thousand Oaks, Calif.: Sage.

Perrow, C. T. (1994). The Limits of Safety The Enhancements of a Theory of Accidents. *Journal of Contingencies & Crisis Management, 2*(4), 212-220.

Peterson, N. G., Mumford, M. D., Borman, W. C., Jeanneret, P. R., Fleishman, E. A., Levin, K. Y., et al. (2001). Understanding work using the Occupational Information Network (O*Net): Implications for practice and research. *Personnel Psychology, 54*(2), 451-492.

Pettersen, K. A., & Aase, K. (2007). Explaining safe work practices in aviation line maintenance. *Safety Science, 46*(3), 510-519.

Pidgeon, N., & O'Leary, M. (2000). Man-made disasters: why technology and organizations (sometimes) fail. *Safety Science, 34*(1-3), 15-30.

Pounds, J., & Isaac, A. (2003). *Validation of the JANUS Technique: Causal Factors of Human Error in Operational Errors* (Technical Report DOT/FAA/AM-

03/21). Washington, D.C.: Federal Aviation Administration-Office of Aerospace Medicine.

Proctor, R. W., & Van Zandt, T. (1994). *Human factors in simple and complex systems*. Needham Heights, Mass.: Allyn and Bacon.

Pyy, P. (2001). An analysis of maintenance failures at a nuclear power plant. *Reliability Engineering & System Safety, 72*(3), 293-302.

Rankin, W. (2007). *MEDA Investigation Process.* Retrieved 4 April 2010, from http://www.boeing.com/commercial/aeromagazine/articles/qtr_2_07/AERO_Q207_article3.pdf

Rasmussen, J. (1982). Human errors. A taxonomy for describing human malfunction in industrial installations. *Journal of Occupational Accidents, 4*(2-4), 311-333.

Rasmussen, J. (1990). The role of error in organizing behaviour. *Ergonomics, 33*(10), 1185 - 1199.

Rasmussen, J. (1997a). Risk management in a dynamic society: a modelling problem. *Safety Science, 27*(2-3), 183-213.

Rasmussen, J. (1997b). Merging paradigms: Decision making, management, and cognitive control. In R. Flin, E. Salas, M. Strub & L. Martin (Eds.), *Decision-making under stress: emerging themes and applications* (pp. 67-81). Aldershot: Ashgate.

Rasmussen, J., & Jensen, A. (1974). Mental procedures in real life tasks: A case study of electronic trouble-shooting. *Ergonomics*(17), 293-307.

Rasmussen, J., Pedersen, O. M., Mancini, G., Carnino, A., Griffon, M., & Gagnolet, P. (1981). *Classification System for Reporting Events Involving Human Malfunctions* (No. RISØ-M-2240). Roskilde, Denmark: Risø National Laboratory, DK 4000 .

Reason, J. (1987). Generic Error Modelling System (GEMS): A cognitive framework for locating common human error forms. In J. Rasmussen, K. Duncan & J. Leplat (Eds.), *New technology and human error*. Chichester: John Wiley & Sons.

Reason, J. (1997). *Managing the Risks of Organizational Accidents*. Aldershot: Ashgate Publishing Ltd.

Reason, J., & Hobbs, A. (2003). *Managing maintenance error : a practical guide*. Aldershot, England Burlington, Vt.: Ashgate.

Reason, J., Manstead, A., Stradling, S., Baxter, J., & Campbell, K. (1990). Errors and violations on the roads: a real distinction? *Ergonomics, 33*(10), 1315 - 1332.

Reason, J., Parker, D., & Lawton, R. (1998). Organizational controls and safety: The varieties of rule-related behaviour. *Journal of Occupational & Organizational Psychology, 71*(4), 289-304.

Reiman, T., & Oedewald, P. (2004). Measuring maintenance culture and maintenance core task with CULTURE-questionnaire--a case study in the power industry. *Safety Science, 42*(9), 859-889.

Reiman, T., & Oedewald, P. (2005). *Exploring the effect of organizational changes on the safety and reliability of maintenance.* Paper presented at the CSNI Workshop on Better Nuclear Plant Maintenance Improving Human and Organisational Performance Ottawa, Canada.

Reiman, T., & Oedewald, P. (2006a). Assessing the maintenance unit of a nuclear power plant - identifying the cultural conceptions concerning the maintenance work and the maintenance organization. *Safety Science, 44*(9), 821-850.

Reiman, T., & Oedewald, P. (2006b). Organisational Culture and Social Construction of Safety in Industrial Organisations. In O. Svenson, I. Salo & e. al. (Eds.), *Nordic Perspectives on Safety Management in High Reliability Organizations: Theory and Applications* (pp. 115-129). Stockholm: Stockholm University Press.

Reiman, T., & Oedewald, P. (2007). Assessment of complex socio-technical systems - Theoretical issues concerning the use of organizational culture and organizational core task concepts. *Safety Science, 45*(7), 745-768.

Reiman, T., Oedewald, P., & Rollenhagen, C. (2005). Characteristics of organizational culture at the maintenance units of two Nordic nuclear power plants. *Reliability Engineering & System Safety, 89*(3), 331-345.

Reinach, S., & Viale, A. (2006). Application of a human error framework to conduct train accident/incident investigations. *Accident Analysis & Prevention, 38*, 396-406.

Roberts, K. H., & O'Reilly, C. A. (1974). Measuring Organizational Communication. *Journal of Applied Psychology, 59*(3), 321.

Roberts, K. H., Rousseau, D. M., & La Porte, T. R. (1994). The culture of high reliability: quantitative and qualitative assessment aboard nuclear-powered aircraft carriers. *The Journal of High Technology Management Research, 5*(1), 141-161.

Roberts, K. H., & Tadmor, C. T. (2002). Lessons learned from non-medical industries: the tragedy of the USS Greeneville. *Qual Safe Health Care, 11*(4), 355-357.

Rochlin, G. I. (1999). Safe operation as a social construct. *Ergonomics, 42*(11), 1549-1560.

Ross, A. J., Wallace, B., & Davies, J. B. (2004). Technical note: measurement issues in taxonomic reliability. *Safety Science, 42*(8), 771-778.

Rubin, R., Palmgreen, P., & Sypher, H. (2004). *Communication Research Measures*. Mahwah, New Jersey: Lawrence Erlbaum Associates.

Sagan, S. D. T. (1994). Toward a Political Theory of Organizational Reliability. *Journal of Contingencies & Crisis Management, 2*(4), 228.

Salas, E., Burke, C. S., Bowers, C. A., & Wilson, K. A. (2001). Team training in the skies: Does crew resource management (CRM) training work? *Human Factors, 43*(4), 641.

Salas, E., DiazGranados, D., Klein, C., Burke, C., Stagl, K., Goodwin, G., et al. (2008). Does Team Training improve Team Performance? A Meta-Analysis. *Human Factors, 50*(6), 903.

Salas, E., Prince, C., Bowers, C. A., Stout, R. J., Oser, R., & Cannon-Bowers, J. A. (1999). A methodology for enhancing crew resource management training. *Human Factors, 41*(1), 161.

Saleh, J. H., & Marais, K. (2006). Reliability: How much is it worth? Beyond its estimation or prediction, the (net) present value of reliability. *Reliability Engineering & System Safety, 91*(6), 665-673.

Sasou, K., & Reason, J. (1999). Team errors: definition and taxonomy. *Reliability Engineering & System Safety, 65*(1), 1-9.

Scarf, P. A., Dwight, R., & Al-Musrati, A. (2005). On reliability criteria and the implied cost of failure for a maintained component. *Reliability Engineering & System Safety, 89*(2), 199-207.

Schaafstal, A., Schraagen, J. M., & van Berlo, M. (2000). Cognitive task analysis and innovation of training: The case of structured troubleshooting. *Human Factors, 42*(1), 75.

Schein, E. H. (1996). Three Cultures of Management: The Key to Organizational Learning. *Sloan Management Review, 38*(1), 9-20.

Senate Standing Committee on Economics. (2008). *Matters relating to the gas explosion at Varanus Island, Western Australia.* Canberra: Commonwealth of Australia.

Sexton, J. B., Thomas, E. J., & Helmreich, R. L. (2000). Error, stress, and teamwork in medicine and aviation: cross sectional surveys. *BMJ, 320*(7237), 745-749.

Shappell, S. A. (2000). *The Human Factors Analysis and Classification System-HFACS*. (Report No. DOT/FAA/AM-00/7). Washington, D.C.: U.S. Department of Transportation, Federal Aviation Administration.

Sharma, K. R., & Kumar, S. (2008). Performance modelling in critical engineering systems using RAM analysis. *Reliability Engineering and System Safety, 93*, 891-897.

Siegel, S. (1956). *Non-parametric statistics for the behavioral sciences* (International Student Edition ed.). Tokyo: McGraw-Hill Kogakusha Ltd.

Sklet, S. (2006). Hydrocarbon releases on oil and gas production platforms: Release scenarios and safety barriers. *Journal of Loss Prevention in the Process Industries, 19*(5), 481-493.

Smith, J. A. T. (2004). Reflecting on the development of interpretative phenomenological analysis and its contribution to qualitative research in psychology. *Qualitative Research in Psychology, 1*(1), 39-54.

Sorensen, J. N. (2002). Safety culture: a survey of the state-of-the-art. *Reliability Engineering & System Safety, 76*(2), 189-204.

Sovacool, B. K. (2008). The costs of failure: A preliminary assessment of major energy accidents, 1907-2007. *Energy Policy, 36*(5), 1802-1820.

Starbuck, W. H., & Milliken, F. J. (1988). Challenger: fine-tuning the odds until something breaks. *Journal of Management Studies, 25*(4), 319-340.

Stasser, G., & Stewart, D. (1992). Discovery of hidden profiles by decision-making groups: Solving a problem versus making a judgment. *Journal of Personality and Social Psychology, 63*(3), 426-434.

Storey, L. (2007). Doing Interpretive Phenomenological Analysis. In E. Lyons & A. Coyle (Eds.), *Analysing Qualitative Data in Psychology* (pp. 53-59). London: Sage Publications Ltd.

Straeter, O., & Kirwan, B. (2002). *Differences between human reliability approaches in nuclear- and aviation-safety.* Paper presented at the IEEE 7th Human Factors Meeting, Scottsdale, Arizona, USA.

Svenson, O., & Salo, I. (2001). Latency and mode of error detection in a process industry. *Reliability Engineering & System Safety, 73*(1), 83-90.

Tabachnick, B. G., & Fidell, L. S. (2007). *Using Multivariate Statistics* (Fifth ed.). Boston: Pearson Education Inc.

Taylor, J. C. (2000). The evolution and effectiveness of Maintenance Resource Management (MRM). *International Journal of Industrial Ergonomics, 26*(2), 201-215.

Taylor, J. R. (2007). Statistics of design error in the process industries. *Safety Science, 45*, 61–73.

Thomas, S. J. (2005). *Creating a Culture Change – A Pathway to Improved Reliability.* Paper presented at the IMC-2005 - The International Maintenance Conference.

TiWest Joint Venture. (2007, 24 February). Engineers-Kwinana-Based*. The West Australian,* p. 19.

Tixier, J., Dusserre, G., Salvi, O., & Gaston, D. (2002). Review of 62 risk analysis methodologies of industrial plants. *Journal of Loss Prevention in the Process Industries, 15*(4), 291-303.

Tjiparuro, Z., & Thompson, G. (2004). Review of maintainability design principles and their application to conceptual design. *Journal of Process Mechanical Engineering Part E, 218*, 103-113.

Todd, Z., & Lobeck, M. (2004). Integrating survey and focus group research: A case study of attitudes of English and German language learners. In Z. Todd, B. Nerlich, S. McKeown & D. D. Clarke (Eds.), *Mixing Methods in Psychology*. Hove and New York: Psychology Press.

Todd, Z., Nerlich, B., McKeown, S., & Clarke, D. D. (Eds.). (2004). *Mixing Methods in Psychology-The Integration of Qualitative and Quantitative Methods in Theory and Practice*. Hove and New York: Psychology Press.

Todinov, M. T. (2004). Setting reliability requirements based on minimum failure-free operating periods. *Quality and Reliability Engineering International, 20*(4), 273-287.

Tomlingson, P. D. (2005). Maintenance Information: Value Added? *Engineering and Mining Journal, 206,* 54-56.

Torp, S., & Grøgaard, J. B. (2009). The influence of individual and contextual work factors on workers' compliance with health and safety routines. *Applied Ergonomics, 40*(2), 185-193.

Tucker, A. L., & Edmondson, A. C. (2003). Why hospitals don't learn from failures: Organizational and psychological dynamics that inhibit system change. *California Management Review, 45*(2), 55-72.

Tucker, A. L., Edmondson, A. C., & Spear, S. (2002). When problem solving prevents organizational learning. *Journal of Organizational Change Management, 15*(2), 122.

Urbina, I. (2010, 6 June). In Gulf, it was unclear who was in charge of rig. *The New York Times,* p. A1.

U.S. Department of Energy. (1999). *DOE Workbook: Conducting Accident Investigations*. (Rev.2), Washington, D.C.: Department of Energy

Vanderhaegen, F. (1999). APRECIH: a human unreliability analysis method - application to railway system. *Control Engineering Practice, 7*(11), 1395-1403.

Varca, P. E., & James-Valutis, M. (1993). The relationship of ability and satisfaction to job performance. *Applied Psychology, 42*(3), 265-275.

Victorian Government Department of Primary Industry (2009). *Petroleum Explorers Guide to Victoria* [Electronic Version]. Retrieved 3 August 2010 from http://new.dpi.vic.gov.au/__data/assets/pdf_file/0012/22332/Vic_PEG_Infrastructure.pdf.

Vogus, T. J., & Welbourne, T. M. (2003). Structuring for high reliability: HR practices and mindful processes in reliability-seeking organizations. *Journal of Organizational Behavior, 24*(7), 877-903.

Wahlstrom, B., Wilpert, B., Cox, S., Sola, R., & Rollenhagen, C. (2002). *Learning organizations for nuclear safety.* Paper presented at the IEEE 7th Conference on Human Factors and Power Plants, Sottsdale, Arizona.

Wall, T. D., Jackson, P. R., & Mullarkey, S. (1995). Further Evidence on Some New Measures of Job Control, Cognitive Demand and Production Responsibility. *Journal of Organizational Behavior, 16*(5), 431-455.

Wallace, B., & Ross, A. (2006). *Beyond Human Error: Taxonomies and Safety Science* Boca Raton, USA: CRC Press.

Wallace, B., Ross, A., Davies, J. B., Wright, L., & White, M. (2002). The creation of a new minor event coding system. *Cognition, Technology & Work, 4*, 1-8.

Wang, H. (2002). A survey of maintenance policies of deteriorating systems. *European Journal of Operational Research, 139*(3), 469-489.

Wani, M. F., & Gandhi, O. P. (1999). *Development of maintainability index for mechanical systems*. *Reliability Engineering & System Safety, 65*(3), 259-270.

Weick, K. E. (1987). Organizational culture as a source of high reliability. *California Management Review, 29*(2), 112.

Wiio, O. A. (1978a). *Contingencies of Organizational Communication-Studies in Organization and Organizational Communication* (No. B-30). Helsinki: The Helsinki School of Economics.

Wiio, O. A. (1978b). *Organizational Communication Studies: The LTT and OCD Procedures.* Paper presented at the Annual Meeting of the International Communication Association, April 25-29, 1978, Chicago, Illinois.

Wiio, O. A., & Helsila, M. (1974). Auditing communication in organizations: a standard survey "LTT Communication Audit". *Finnish Journal of Business Economics, 4*, 303-315.

Wilpert, B. (2007). Psychology and design processes. *Safety Science, 45*, 293-303.

Wright, P. (1974). The harassed decision maker: Time pressures, distractions, and the use of evidence. *Journal of Applied Psychology, 59*(5), 555-561.

Wu, T.-C., Chen, C.-H., & Li, C.-C. (2008). A correlation among safety leadership, safety climate and safety performance. *Journal of Loss Prevention in the Process Industries, 21*(3), 307-318.

Yang, B., Watkins, K. E., & Marsick, V. J. (2004). The construct of the learning organization: Dimensions, measurement, and validation. *Human Resource Development Quarterly, 15*(1), 31-55.

Zequeira, R. I., & Berenguer, C. (2006). Periodic imperfect preventive maintenance with two categories of competing failure modes. *Reliability Engineering & System Safety, 91*(4), 460-468.

Zohar, D. (1980). Safety climate in industrial organizations: Theoretical and applied implications. *Journal of Applied Psychology, 65*(1), 96-102.

Zohar, D. (2002a). The effects of leadership dimensions, safety climate, and assigned priorities on minor injuries in work groups. *Journal of Organizational Behavior, 23*, 75-92.

Zohar, D. (2002b). Modifying supervisory practices to improve subunit safety: A leadership-based intervention model. *Journal of Applied Psychology, 87*(1), 156-163.

Zohar, D. (2008). Safety climate and beyond: A multi-level multi-climate framework. *Safety Science*, *46*(3), 376-387.

Zohar, D., & Luria, G. (2003a). Organizational meta-scripts as a source of high reliability: The case of an army armoured brigade. *Journal of Organizational Behavior, 24*(7), 837.

Zohar, D., & Luria, G. (2003b). The use of supervisory practices as leverage to improve safety behavior: A cross-level intervention model. *Journal of Safety Research, 34*(5), 567-577.

Zohar, D., & Luria, G. (2005). A multilevel model of safety climate: Cross-level relationships between organization and group-level climates. *Journal of Applied Psychology July, 90*(4), 616-628.

Appendix A: Templates used to Collect Data from Interviewees

Curtin University of Technology

School of Psychology

Curtin University of Technology

Project: Preventing Failures and Creating Reliability in Maintenance

Incident Location: ______________ Interview Code: ______________

Incident Date: ______________ Incident Time: ______________

Maintenance Crew: ______________________

Crew Type:
- ☐ Electrical ☐ Mechanical ☐ Inlec
- ☐ Company Crew ☐ Contractor Crew ☐ Day Crew ☐ Night Crew

Brief Description of the Incident:

Cover Sheet

HFIT Worksheet - Action Errors

Interview Code:____________________

Location ____ ***Interview Date***____________________

☐ **1. Omission**	☐ **2. Timing**	☐ **3. Sequence**	☐ **4. Quality**	☐ **5. Selection**
☐ Was the task not performed at all?	☐ Was the action carried out for too long or too short?	☐ Was an action repeated, but should not have?	☐ Was an action carried out too little or too much?	☐ Did someone select the wrong equipt.or use the wrong parts?
☐ Was one particular bit missed out?	☐ Was the action carried out too early or too late?	☐ Was one or more steps in the wrong order?	☐ Was a wrong action carried out or in the wrong direction?	

☐ **6. Information**		☐ **7. Violations (Procedures Not Followed)**	
☐ Was information not transmitted or recorded?	☐ Was incorrect information given in a message?	☐ Did someone violate a rule without intending?	☐ Was this the first time the person had violated this rule ?
☐ Was unclear information transmitted or recorded?	☐ Was incomplete information given?	☐ Was this rule often violated by other personnel?	☐ Was this violation accepted by the company?

NOTES:

HFIT Worksheet - Situation Awareness **Interview Code:___________________**

Location ___________________________________ ***Interview Date***_________________

8. Attention Failure	9. Detection & Perception	10. Memory	11. Interpretation	12. Decision Making
Was the person distracted, interrupted or pre-occupied elsewhere?	Was a warning signal missed?	Was a stage or step in the task forgotten?	Did someone hear or see information correctly but not understand its meaning?	Was an incorrect or inappropriate solution applied?
Was the person's attention divided across several tasks?	Was something seen mistaken or mis-identified?	Did the person lose their place?		Was a partial solution applied?
Was the person focused on one aspect of the job?	Was information misheard?			Did someone fail to consider other relevant factors?

13. Assumption		14. Response Execution
Did someone assume that previous tasks were carried out?	Did someone assume that they were fixing the correct parts or system?	Did force of habit lead to a wrong action (eg, twist in the wrong direction)?
Did someone assume that equipment & location were correct?	Did someone assume that correct procedures were being used?	Did someone have a lack of manual precision (eg from cold fingers)?

NOTES:

Page SA 1

HFIT Information Worksheet - Threats **Interview Code:___________________**

15. HUMAN - MACHINE INTERFACE (Alarms & Devices)

System-Equipment Interface	System-Equipment Interface	System-Equipment Interface	**Alarms**	**Error-Tolerant Systems**	**Protective Systems**
Were devices bypassed or disabled to meet time constraints or make the job easier?	Was an attempt made to service equipment without turning it off?	Was equipment needed for the job inaccessible or unavailable?	Were there more alarms than the operator could cope with in the situation?	Was the error or fault in system detectable before the incident (was there a warning before the problem started)?	Was PPE required?
Were devices or controls disabled because of a fault?	Were the operating limits of equipment exceeded?	If available, were the appropriate tools or equipment used for the job?	Are alarm displays & images easily identified?	Was the system designed so that the mistake or error could be corrected before an incident occurred?	Was PPE effective?
Were devices or controls disabled in the past and no action taken to resolve?	Were tools or equipment placed in a hazardous position?	Were the tools or equipment properly prepared prior to the job?	Do operators trust alarm systems?		Was PPE available?
Were protective devices fitted (guards, interlocks)?	Were the tools or equipment needed to perform the task wrongly calibrated?	Were the tools or equipment needed for the job defective or unsafe?	Are alarms prioritised?		Was the use of PPE ignored?
	Was there a task-based risk assessment for operating this equipment?		Are alarm and texts relevant for the task they are associated with?		Was PPE not used because it makes tasks more difficult?
			Are the alarm signals short and distinct?		Were guards or protective devices ineffective?
					Were the warning systems effective?
					Was equipment not fully isolated- people exposed to danger?
					Were safety devices present, but did not act quickly enough?

NOTES:

HFIT Information Worksheet - Threats **Interview Code:___________________**

16. PLANT, PARTS TOOLS AND EQUIPMENT (Design & Maintenance)

Design of Tools and Equipment	**System Design**	System Design	**Plant and Parts**	**Maintenance and Condition Monitoring**	Maintenance and Condition Monitoring
Was the design or structure inadequate?	Is the equipment in the incident adequately labelled?	Could controls involved in the incident be better placed or have greater precision?	Was there sufficient physical and visual access to the facility to read gauges, open valves, install parts?	Was there a system in place for reporting faults and damage?	Was maintenance and CM carried out correctly?
Were selected components or materials inadequate?	Are labels legible under all conditions?	Was the equipment needed for this job unreliable or had a history of defects?	Was the plant design too complex: fault finding is difficult, tasks are error-prone?	Did the equipment have a maintenance or CM testing schedule?	Was the needed repair work communicated to the right person?
Were unauthorised modifications carried out?	Are labels clearly understood (relation to controls, degree of accuracy, relationship of readings to task)?	Was the incident related to use of non-standard equipment?	Is the plant user-friendly: can components be installed in the wrong orientation, etc	Was the time interval between scheduled maintenance adequate?	Was there sufficient time given for the maintenance or repair work?
Was the design or modification carried out as intended?	Was any control activated by accident?	Does the equipment have poor readability or	Is there consistency between similar pieces of equipment?	Was equipment overdue for maintenance or CM?	Were the parts used in repair or maintenance adequate?
Was the field walk-through to carry out design inadequate?	Does the data shown need interpretation before being used?		Were substitute parts used that were inappropriate or did not meet spec.?	Was maintenance or CM done as planned but did not detect or correct the problem?	
			Do parts deform or break easily during installation?		

NOTES:

HFIT Information Worksheet - Threats

Interview Code:____________________

17. WORK ENVIRONMENT			**18. COMMUNICATION**		
Weather Conditions	**Internal Environment**	**Manual Handling**	**Location of Comm. Problem**	**Communication Misunderstood**	**Barriers to Good Communication**
Did extreme temperatures affect someone's ability to perform the task?	Did temperature, humidity or ventilation create difficult conditions?	Did manual handling problems contribute to the incident?	Was there poor communication: within the team?	Was there a lack of communication?	Was a message distorted because it passed through several people?
Did rain or wind create difficult conditions?	Did vibration or noise create difficult conditions?	Did repeated handling contribute to the incident?	" between shifts or rotations?	Was communication too late?	Did the sender and receiver have a different understanding of message content?
Did poor or inappropriate lighting create difficulties or dangerous conditions?	Did poor lighting create difficulties or dangerous conditions?	Did keeping the same position for a long time contribute to the incident?	" between the supervisor and the team?	Was the message misunderstood because it was too long or short?	Was comm. through formalised channel-not allowing discussion/feedback
Did weather make communication difficult?	Was there enough space to work comfortably?	Did heavy lifting contribute to the incident?	" between the supervisor and management?	Was the message misunderstood because of unknown words?	Was message through only one medium and could be mis-interpreted?
	Did poor house-keeping play a role in the incident?	Did bulky, unstable or unpredictable loads contribute to the incident?	" with other teams or departments?	Were verbal messages confirmed?	Did management encourage direct communication with them?
	Did any of the above make communication difficult?		" between onshore and offshore personnel?	Was the value of communication taken seriously?	
			" between companies?	Were there problems with comm. equipt.?	

NOTES:

HFIT Information Worksheet - Threats **Interview Code:___________________**

19. TEAM WORK

Shared Situation Awareness (specific)	**Shared Situation Awareness (general)**	**Team Decision Making**	**Roles and Responsibilities**	**Co-operation**	Co-operation
Did team members tell each other about the plant (changing systems)?	Do team members regularly share job information?	Was the team able to get information needed to define problem & its cause	Are job descriptions worked out for team members?	Had the person worked with other team members before?	Are team members often involved in conflicts?
Did everyone share information about the environment (e.g., hazards)?	Did everyone ask the questions that they should have?	Did the team assess the risks and select the best response?	Were team members aware of their job instructions?	Did the team establish active participation in fulfilling the tasks?	Does the team work well to create a good work climate?
Did everyone know enough about what others were doing?	Did everyone listen to the instructions and discussions?	Did anyone doubt their ability to make decisions or voice concerns?	Were the reporting relationships clear?	Are crew members competitive with each others and other teams?	Do team members check each others work?
Did everyone know how their actions influenced each other?	Did people provide appropriate feedback to other team members?	Did the team agree on the decision?	Was it clear who was responsible for each part of the task?	Do members accept others and understand their personal condition?	Do team members feel troubled by the organisation or their supervisors?
	Were any non-verbal signals ignored?	Was the team able to make a decision themselves?	Did the supervisor ensure personnel were phys.& psych. able to do the task?	Are team members supportive towards each other?	
		Was the team able to generate multiple responses to a problem?	Do team members understand the jobs and roles of other team members?	Does the team work together & cooperate to reach targets?	
		Did they collectively bypass rules?			

NOTES:

HFIT Information Worksheet - Threats **Interview Code:____________________**

☐ ***20. SUPERVISION AND LEADERSHIP***

☐ **Level of Supervision**	☐ **Instruction**	☐ **Leadership**	Leadership	Leadership
☐ Was the supervisor present at the job?	☐ Were the duties and tasks clearly explained?	☐ Does the supervisor advocate his/her own position?	☐ Did the supervisor intervene if task completion deviated from standards?	☐ Did the supervisor distribute tasks effectively?
☐ Was the supervisor only present at the planning stage?	☐ Was there a pre-job briefing by a supervisor or person close to the work?	☐ Did the supervisor take command when situation required it?	☐ Did supervisor consult the team if non-standard procedures were to be used?	☐ Was the supervisor over-stretched regarding workload?
☐ Was supervisor only present for safety aspects of the job?	☐ Did the supervisor provide a work-site walk-through if it was needed?	☐ Did the supervisor involve the team in decision making, problem solving, and risk assessment?	☐ Did supervisor check that performance standards were being complied with?	☐ Did the supervisor allocate enough time to complete the tasks?
☐ Was the supervisor only present for part of the job?	☐ Was there a conflict between information given by supervisor and work orders?	☐ Did the supervisor positively motivate his workgroup to work effectively?	☐ Did the supervisor clearly state the goals of the job?	☐ Did the supervisor imply haste?
☐ Was the supervisor too involved in the running of the job?	☐ Was the progress of the job adequately monitored?	☐ Did the supervisor provide adequate feedback on performance?	☐ Did the supervisor inform or consult the team before changing the plans?	☐ Was the supervisor fair with discipline?
	☐ Did the supervisor carry out final check after job completion?			

NOTES:

HFIT Information Worksheet - Threats

Interview Code:___________________

21. ORGANISATIONAL CULTURE			**22. COMPETENCE & TRAINING**		
Management Commitment	**Learning Organisation**	**Reporting Culture/ Incentives**	**Competence Level**	**No Training**	**Training Effectiveness**
Does management make work quality a priority ahead of getting work done as quickly as possible?	Is there a way of feeding back information about quality problems?	Are employees ever penalised for expressing concerns?	Did everyone have the required skills to perform the job.?	Were personnel given training in the platform's systems?	Did the training have adequate goals?
Does management take time to be familiar with what is happening at the work-site?	Is this used to report quality problems on a regular basis?	Do people believe that reporting minor incidents causes too much hassle?	Did everyone have the qualifications to perform the job?	Was training given for this type of task?	Were the training materials understood by the people involved?
Is there a good relationship between management and the workforce?	Has a similar incident occurred in the organisation?	Do people believe that a problem should not be reported without a solution?	Was anyone out of practice in performing the job?	Was the need for training recognised?	Did training include a variety of techniques
Does management demonstrate a positive attitude to safety?	Does management address concerns of the workforce ?	Do employee concerns usually reach management?	Did anyone need coaching from a supervisor or experienced co-worker?	Was a conscious decision made to forego training?	Was the opportunity for practical training provided?
Does management communicate their safety beliefs to workers?	Does management generally respond to employee concerns in a timely manner?	Did management create production targets that may have led to the incident?		Were new work methods introduced and training given?	Was the training presented clearly?
		Did management's financial incentives lead to the incident?		Was the importance of training recognised by the trainee?	Was refresher training provided?
		Were there safety incentives that may have prevented incident reporting?			Does the training include competence assessment?

NOTES:

HFIT Information Worksheet - Threats **Interview Code:__________________**

23. PROCEDURES

Procedure was not used
- Does a procedure exist?
- Was a procedure not used because it was difficult to obtain?
- Was a procedure difficult to use at the work-site?
- Was procedure known of by the person doing the work?
- Was use of procedure not required but would have prevented the incident?
- Was procedure required but considered unnecessary?

Procedure used incorrectly
- Was the level of detail appropriate for the skills of the person?
- Are the language and instructions clear and familiar acronyms used?
- Do procedures conform to company guidelines?

Procedure wrong or incomplete
- Was the wrong procedure used?
- Was the wrong revision or version
- Was the procedure appropriate for the job?
- Did the procedure describe the safest way of doing the job?

24. WORK PREPARATION (& Planning)

Work package inadequate
- Are there written guidelines for preparing work packs?
- Were instructions for preparing work packs followed?
- Are guidelines for preparing work packs clear?
- Were instructions and guidelines for preparing work packs known to all relevant personnel?

Work permit inadequate
- Was a work permit raised for this task?
- Were guidelines followed in raising work permits?
- Are guidelines for raising work permits understandable ?
- Was an adequate investigation of plant conducted before raising work permits?
- Were personnel correctly informed after the work was finished?

Work planning inadequate
- Was the workload on staff acceptable (time for the work and number of people)?
- Was there a proper walkthrough for the team before starting the work?
- Was the work properly prioritised?
- Were the work instructions adequate, and correctly worked out?

NOTES:

HFIT Information Worksheet - Threats **Interview Code:____________________**

25. JOB FACTORS			***26. PERSON FACTORS***		
Task Characteristics	**Work Pressure**	**Staffing**	**Physical Capability & Condition**	**Stress**	**Motivation**
Was task too complex or too confusing?	Was work efficiently organised by supervisors?	Were enough workers assigned to the job?	Did someone's physical condition contribute to the incident?	Was someone affected by personal problems?	Was there pressure from management to finish the work?
Was task very boring?	Was previous job delayed causing time pressures?	Was job correctly divided between people according to skills, etc?	Did fatigue due to workload affect the ability to do the task?	Was someone frustrated by the task or his/her job?	Was everyone interested in the job and motivated to work effectively?
Was task executed again and again?	Was enough time allocated to complete the job?	Were appropriate personnel available?	Did fatigue due to lack of sleep affect the ability to do the task?	Was morale high in the crew?	Was there pressure on someone from schedule deadlines?
Was the task executed differently from normal	Was scheduling of tasks efficient?		Did shift work affect the task execution?	Was someone unsure of his/her ability to complete the job successfully?	Did workmates have a negative effect on anyone?
Was task on new or on modified equipment?	Was there enough time to carry out job safely and correctly?		Did fatigue due to sensory overload affect the ability to do the task?	Did someone have to make difficult judgements?	Was safe, quality work demonstrated?
If more than one job was going; was it difficult to combine jobs?			Were they able to coordinate required actions? (slow reaction time)	Did incident occur during extreme concentration?	Did financial incentives have any effect?
Did the main job leave time for side jobs?				Was the person very bored doing the task?	Was someone under threat of job loss?

NOTES:

HFIT Information Worksheet - Threats **Interview Code:___________________**

27. POLICIES, STANDARDS AND MANAGEMENT SYSTEMS

PSP Development Inadequate	PSP Development Inadequate	**PSP Implementation Inadequate**	PSP Implementation Inadequate	PSP Implementation Inadequate
Were there management docs associated with the task that led to the incident?	Have changes been made to drawings/diagrams that are confusing?	Is it made clear that management documents should be followed?	Was there a defined person responsible for PSPs?	Did the responsible person reinforce the PSPs or correct non-compliant behaviour?
Were the management systems and docs not followed because they were difficult to use or understand?	Are drawings representative and timely?	Were the PSPs communicated adequately to relevant personnel?	Did the responsible person monitor that the PSPs were being used correctly?	Are there any consequences if the personnel do not use the management documents?
Is the content of the management system correct?		Were the PSPs translated into appropriate languages?	Did the supervisor have a good understanding of the PSPs?	
		Were the PSPs integrated into the training?		

NOTES:

Appendix B: Approval of the Curtin University Ethics Committee

Curtin University of Technology

memorandum

To	Prof Clare Pollock, Psychology
From	A/Professor Stephan Millett, Chair, Human Research Ethics Committee
Subject	Protocol Approval **HR 147/2007**
Date	18 February 2008
Copy	Ari Antonovsky Psychology Graduate Studies Officer, Faculty of Health Sciences

Office of Research and Development

Human Research Ethics Committee

TELEPHONE 9266 2784
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EMAIL hrec@curtin.edu.au

Thank you for providing the additional information for the project titled "*The Role of Human factors in Maintenance Workgroup performance in petroleum industry operations*". The information you have provided has satisfactorily addressed the queries raised by the Committee. Your application is now **approved**.

Reviewer 1: Approved with minor amendment. The project is well conceived and structured. I make one You have ethics clearance to undertake the research as stated in your proposal.

- The approval number for your project is **HR 147/2007.** *Please quote this number in any future correspondence.*
- Approval of this project is for a period of twelve months **19-02-2008** to **19-02-2009**. To renew this approval a completed Form B (attached) must be submitted before the expiry date **19-02-2009**.
- If you are a Higher Degree by Research student, data collection must not begin before your Application for Candidacy is approved by your Faculty Graduate Studies Committee.
- The following standard statement **must be** included in the information sheet to participants:
  This study has been approved by the Curtin University Human Research Ethics Committee (Approval Number HR 147/2007). The Committee is comprised of members of the public, academics, lawyers, doctors and pastoral carers. Its main role is to protect participants. If needed, verification of approval can be obtained either by writing to the Curtin University Human Research Ethics Committee, c/- Office of Research and Development, Curtin University of Technology, GPO Box U1987, Perth, 6845 or by telephoning 9266 2784 or by emailing hrec@curtin.edu.au.

Applicants should note the following:

It is the policy of the HREC to conduct random audits on a percentage of approved projects. These audits may be conducted at any time after the project starts. In cases where the HREC considers that there may be a risk of adverse events, or where participants may be especially vulnerable, the HREC may request the chief investigator to provide an outcomes report, including information on follow-up of participants.

The attached **FORM B** should be completed and returned to the Secretary, HREC, C/- Office of Research & Development:
When the project has finished, or

- If at any time during the twelve months changes/amendments occur, or
- If a serious or unexpected adverse event occurs, or
- 14 days prior to the expiry date if renewal is required.
- An application for renewal may be made with a Form B three years running, after which a new application form (Form A), providing comprehensive details, must be submitted.

Regards,

A/Professor Stephan Millett
Chair Human Research Ethics Committee

Appendix C: Information Sheet to Explain the Purpose of this Research

Curtin University of Technology

School of Psychology

Bentley, Western Australia

Call for Volunteers

Recognising the Human Factors in Maintenance at [the company]

Thanks for your interest in our project. This information sheet will explain why we are doing this project, and how it may help you in your job and help [the company] become a better place to work.

Why is this project important?

This project will examine the human and organisation factors in your workplace, and their role in creating maintenance reliability. The information will be used to make [company] workplaces more-user friendly and to eliminate the factors that cause breakdowns in the workplace.

By volunteering to be part of this study, the important information that you can provide will help us to determine what workplace issues make the job of maintainers at [the company] more effective. Many times the goals and pressures create the basis for mistakes and frustration. People working at the 'coalface' experience this and are the best people to feed back examples of where this is happening.

Who is conducting this research?

Specialists in human factors in the School of Psychology at Curtin University of Technology have developed this project with the support of [the company] Maintenance Strategy group. The principal researcher, Ari Antonovsky, is an engineer with 15 years experience in maintenance reliability in the WA mining industry.

What will you be doing for this survey?

We are asking you to participate in a short interview (about 50 minutes).

The interviews will be at [company headquarters] if you are based in Perth and at site if you are based at the Process Plant. All interviews will involve only yourself and a researcher from Curtin University. No information from you goes directly back to [the company].

Examples of the types of questions you will be asked are:

- Was a particular part of a task missed out?
- Did someone assume that equipment and location were correct?
- Was a procedure not used because it was difficult to obtain?

Who can participate in this study?

We are looking for anyone in the maintenance, operations or supervisory areas who have first-hand knowledge of work that did not 'go-to-plan', or later caused maintenance 'headaches'.

How will your information be used?

The responses of all the people interviewed will be collected together to determine which of the human and workplace issues are most important to maintenance reliability at [the company].

All employees participating in this project will be COMPLETELY ANONYMOUS.

- No personal information will be asked for in the interview;
- No [company] staff will be present at the interview;
- The information that [the company] receives will be grouped together to ensure that individuals cannot be identified. All information will be held confidentially by Curtin.
- Note that you can change your mind at any time and chose not to continue.

What you need to do to assist this project

- All you need to do is to reply to this note by e-mail.
- A member of the research team will then contact you to set up a meeting. We will ask when your best availability is. That's all there is to it.
- If you have any questions about the project, please contact one of the people below.

Ari Antonovsky
ari.antonovsky@postgrad.curtin.edu.au
041 312 7935

Prof Clare Pollock
clare.pollock@curtin.edu.au
08 9266 7867

This study has been approved by the Curtin University Human Research Ethics Committee (Approval Number HR 147/2007. If needed, verification of approval can be obtained either by writing to the Curtin University Human Research Ethics Committee, c/- Office of Research and Development, Curtin University of ***Technology, GPO Box U1987, Perth, 6845 or by telephoning 9266 2784 or emailing hrec@curtin.edu.au***

Appendix D: Raw Data Derived from Interviews with Maintenance Personnel

Interview Code	Interview Date	Incident Date	Type	Position Level	ACTION ERRORS Omis	Time	Seq	Qual	Sel	Info	Viol	SITUATION AWARENESS Att	Det	Mem	Int	Dec	Ass	Exec	THREATS HMI	Design	Environ	Comm	Team	Superv	OrgCult	Skill	Proced	Prep	Job	Person	ManDo	Potential Severity
KGP1	2/04/2008	Aug-2007	Mech	Supervisor	1	1	0	0	0	1	0	1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	1	0	0	1	0	Med
KGP2	2/04/2008	Apr-2008	Elect	Technician	1	1	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	1	1	0	0	0	0	High
KGP3	2/04/2008	Jan-2008	Mech	Fitter	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	1	1	0	1	0	0	1	1	0	0	High
KGP4	3/04/2008	May-2006	Mech	Supervisor	0	0	0	1	0	0	0	1	1	0	1	1	1	1	0	1	0	1	0	1	0	1	0	0	1	1	0	High
KGP5	3/04/2008	Mar-2008	Mech	Fitter	0	0	0	0	0	1	0	1	1	0	1	1	1	0	0	1	0	1	0	1	1	1	1	1	0	0	0	High
KGP6	3/04/2008	Oct-2006	Elect	Technician	0	0	0	0	0	1	0	0	0	0	0	1	1	0	1	1	1	1	0	0	0	1	0	0	1	0	0	High
KGP7	3/04/2008	Mar-2008	Mech	Fitter	1	0	0	0	0	0	0	0	1	1	0	0	1	0	0	1	1	1	0	0	0	1	0	1	0	0	0	Low
KGP8	3/04/2008	Jun-2004	Elect	Technician	1	0	0	0	1	1	0	1	1	0	0	0	1	0	1	1	0	0	0	1	1	0	1	1	1	1	1	Med
KGP9	3/04/2008	Jan-1998	Mech	Estimator	1	0	0	1	0	0	0	0	1	0	0	0	1	0	0	1	0	1	0	1	1	1	0	1	1	1	1	High
KGP10	4/04/2008	Feb-2008	Mech	Technician	1	1	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	1	1	1	1	0	0	0	0	0	High
KGP11	4/04/2008	Jun-2006	Elect	Supervisor	1	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	0	0	1	0	Med
MMG1	18/02/2008	Mar-2007	Mech	Coordinator	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	1	1	1	0	0	1	1	1	0	1	0	Low
MMG2	20/02/2008	Feb-2008	Mech	Coordinator	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1	1	1	0	0	1	1	1	1	0	0	Med
MMG3	22/02/2008	Nov-2007	Elect	Coordinator	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	1	Med
MMG5	19/03/2008	Oct-2004	Mech	Coordinator	0	1	0	1	1	0	0	1	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	1	1	0	1	High
CCG1	18/04/2008	Oct-2006	Mech	Supervisor	1	0	0	0	1	1	1	0	1	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	Low
MMG4	30/07/2008	Nov-2006	Mech	Planner	1	1	0	0	0	1	1	0	0	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	1	High
MMO1	27/02/2008	Jul-2007	Mech	Coordinator	1	0	0	0	0	1	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	Med
MMO2	27/02/2008	Jan-2008	Mech	Coordinator	0	1	0	1	0	0	0	0	1	0	0	1	0	0	0	1	0	1	0	0	0	1	1	0	0	0	1	Med
MMO3	29/02/2008	Sep-2007	Mech	Technician	1	0	0	0	0	1	0	1	0	1	0	0	1	0	0	0	0	1	1	0	0	0	1	1	0	0	0	Med
MMO4	7/03/2008	Jul-2007	Mech	Coordinator	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	1	0	1	Med
MMO5	10/03/2008	Feb-2007	Mech	Technician	0	1	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	1	0	0	0	0	1	1	0	0	0	High
MMO6	10/03/2008	Feb-2008	Elect	Coordinator	0	1	0	0	0	1	1	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	1	1	0	1	Low
MMO7	12/03/2008	Jul-2007	Mech	Technician	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0	1	Low
MMO8	17/03/2008	Jul-2007	Elect	Technician	0	1	0	0	1	0	0	0	0	0	1	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	Med
MMO9	28/03/2008	Sep-2007	Elect	Technician	1	0	0	1	0	0	0	1	0	1	0	0	0	0	1	0	1	0	1	1	0	0	0	0	1	0	1	Med
COS1	4/08/2008	Jul-2008	Elect	Technician	1	0	0	0	0	1	1	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	1	0	1	0	1	Low
COS2	4/08/2008	Feb-2008	Mech	Technician	1	0	0	0	1	0	0	0	1	0	0	1	1	0	0	1	1	1	0	1	0	1	0	0	1	1	0	Low
COS10	5/08/2008	Jan-2005	Mech	Technician	1	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	Med
COS3	5/08/2008	Jul-2008	Elect	Technician	1	0	0	0	0	0	0	1	1	0	0	0	1	1	1	0	0	0	0	0	1	0	1	0	0	0	0	Med
COS4	5/08/2008	Mar-2008	Mech	Technician	0	1	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	1	0	0	1	0	0	0	1	0	1	High
COS5	5/08/2008	Jun-2003	Mech	Coordinator	0	1	0	0	0	0	1	0	0	0	0	1	1	0	0	1	0	0	0	0	1	1	0	0	0	0	0	Med
COS6	5/08/2008	Apr-2007	Elect	Technician	0	1	0	0	1	0	0	0	0	0	0	1	1	0	0	1	1	1	0	0	0	0	1	0	1	0	0	Med
COS7	5/08/2008	Jan-1999	Mech	Supervisor	0	0	0	1	0	1	1	0	1	0	0	1	1	0	0	1	0	1	0	0	0	1	0	0	0	0	0	High
COS8	5/08/2008	Aug-2007	Elect	Technician	0	0	0	0	1	1	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	1	0	0	0	1	Med
COS9	5/08/2008	Jul-2008	Elect	Technician	1	0	0	0	1	1	0	1	1	0	0	0	1	0	0	1	0	1	0	0	1	0	0	1	0	0	0	Low
COS11	6/08/2008	Feb-2007	Elect	Technician	0	1	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	1	1	0	1	1	1	0	0	0	0	Low
COS12	6/08/2008	Jan-2005	Elect	Supervisor	1	0	0	1	1	0	1	0	0	0	0	1	1	0	1	1	0	1	0	1	0	0	0	0	0	1	1	High
				Totals	22	14	0	10	12	17	7	12	15	6	4	21	30	2	5	27	11	25	9	11	15	16	17	15	14	8	15	

Appendix E: Scales Used in the Survey in Study 3

Work Design Questionnaire (Morgeson & Humphrey, 2006, p.1338):

Problem Solving scale:

1. The job involves solving problems that have no obvious correct answer.
2. The job requires me to be creative.
3. The job often involves dealing with problems that I have not met before.
4. The job requires unique ideas or solutions to problems.

Melbourne Decision-Making Questionnaire (Mann, Burnett, Bradford & Ford, 1997, p.12):

Vigilance scale:

1. I like to consider all of the alternatives.
2. I try to find out the disadvantages of all alternatives.
3. I consider how best to carry out a decision.
4. When making decisions I like to collect a lot of information.
5. I try to be clear about my objectives before choosing.
6. I take a lot of care before choosing.

Organisational Communication Development Audit Questionnaire (OCD/2) (Greenbaum, Clampitt, & Willihnganz, 1988, p.276):

Each question is answered on a five-point scale as follows: 1 is very dissatisfied (very little); 2 is dissatisfied (little); 3 is cannot say; 4 is satisfied (much), 5 is very satisfied (very much).

A. Are you satisfied or dissatisfied with communication and the availability of information in your organization?

B. How much information about your work and organization do you get now from:

1. Supervisors and management	2. Shop stewards	3. Fellow employees
4. Bulletin boards	5. Newsletters/house organ	6. Staff meetings
7. Memorandums and reports	8. (Organization specific)	9. Computer-based information systems

D. What is the amount of information you receive now about the following job items?

1. Economic situation of the organisation	2. Employment situation	3. My own work
4. Changes in production	5. Training and courses	6. Employee benefits
7. Sales	8. Organisational changes	

Appendix F: Maintenance Workplace Questionnaire – Form Sent to Participants

Faculty of Health Sciences
Curtin University of Technology

Your Opinions on the [Company] Maintenance Workplace

Thanks for taking the time to fill in our survey of your experience as a maintainer at [the company]. The following will explain why we are doing this questionnaire, and how it could help you in your job and make [the company] a better place to work.

Why is this survey important?

We need your help to examine the organisational factors in your workplace, and how they help or get in the way of good maintenance work. The information will be used to make [company] workplaces more effective and user-friendly for maintainers.

Why should you participate?

This is your chance to tell us how you feel about your workplace, and how various issues affect your work. People like you who work at the 'coalface' are the best people to tell us what is really happening out there. Each person filling in this survey contributes to improving the systems that link people to complex plants & equipment.

What will you be doing for this survey?

All you need to do is to complete the following questions. This should take about 15 minutes.
Then hand the form back to the meeting coordinator or send it back via the internal mail system to:

Ari Antonovsky at Mail drop WP 03-12L.

Who is conducting this research?

Specialists in Human Factors at Curtin University have developed this survey, with support from [the company]. The principal researcher, Ari Antonovsky, is a maintenance engineer with 15 years experience in maintenance in the WA mining industry. This study forms part of his PhD at Curtin University. Clare Pollock has 20 years of research experience in Human Factors and Safety.

How will your information be used?

The completed questionnaires will be analysed to find out what the workplace is like for [company] maintainers. All employees participating in this project will be completely anonymous.

- Your responses will only be identified by a code number;
- No personal information will be asked for;
- All information will be held by Curtin University, not by [the company].

By completing the survey and handing it in, you are agreeing to let us use the information for research purposes.

Thanks for participating. If you have any questions about the survey please contact either of the people below.

Ari Antonovsky	Prof Clare Pollock
ari.antonovsky@postgrad.curtin.edu.au	clare.pollock@curtin.edu.au
041 312 7935	**08 9266 7867**

This study has been approved by the Curtin University Human Research Ethics Committee (Approval Number HR 147/2007. If needed, verification of approval can be obtained either by writing to the Curtin University Human Research Ethics Committee, c/- Office of Research and Development, Curtin University of Technology, GPO Box U1987, Perth, 6845 or by telephoning 9266 2784 or emailing hrec@curtin.edu.au

Curtin University of Technology

Preventing Failures and Creating Reliability in Maintenance
Maintenance Workplace Questionnaire

Curtin Univ. Code____________________
(Office Use)

Please tick the appropriate box:

Your Usual Workplace: ❑ GP1 ❑ GP2 ❑ GP3 ❑ Process Plant
❑ FP1 ❑ FP2 ❑ FP3

If you work in the Process Plant:
Work Area: ❑ PP1 ❑ PP2 ❑ PP3

❑ Other: Where?________________________________

Workgroup type: ❑ Core Crew ❑ Major Maintenance ❑ Shutdown Crew

❑ Other: Which?________________________________

Work Category: ❑ Electrical/Inlec ❑ Mechanical

Length of Time at this Facility: ❑ Less than 3 months ❑ 3-12 months
❑ 1-3 years ❑ 3-10 years ❑ More than 10 years

Total Time in the Resource Industry: ❑ Less than 3 months ❑ 3-12 months
❑ 1-3 years ❑ 3-10 years ❑ More than 10 years

Are you employed by:
❑ [the company] ❑ Contractor

DIRECTIONS:

For each question, circle the number from 0 to 4 that best expresses your opinion and return the questionnaire by [the company] internal mail to:

Ari Antonovsky

Mail drop WP 03-12L

Section 1: Design & Maintenance section

	Thinking of the machines and equipment that you work on:	Never	Hardly Ever	Sometimes	Often	Always
1	Are the structures and designs of plant equipment adequate ('fit for purpose')?	0	1	2	3	4
2	Are the parts, spares, and materials used adequate ('fit for purpose')?	0	1	2	3	4
3	Do you have sufficient access to equipment for maintenance?	0	1	2	3	4
4	Is equipment ever overdue for maintenance or Condition Monitoring?	0	1	2	3	4
5	Do you ever encounter problems with modifications?	0	1	2	3	4
6	Do you ever work on non-standard equipment (e.g., unexpected or confusing designs)?	0	1	2	3	4
7	Does the plant design allow parts to be installed easily?	0	1	2	3	4
8	Do you find that equipment is accurately labelled for maintenance work?	0	1	2	3	4

Section 2: Problem-solving section

	Thinking of your usual jobs around the facility:	Strongly Disagree	Disagree	Hard to say	Agree	Strongly Agree
9	The job involves solving problems that have no obvious correct answer.	0	1	2	3	4
10	The job requires me to be creative.	0	1	2	3	4
11	The job often involves dealing with problems that I have not met before.	0	1	2	3	4
12	The job requires unique ideas or solutions to problems.	0	1	2	3	4
13	I like to consider all of the alternatives.	0	1	2	3	4
14	I try to find out the disadvantages of all alternatives.	0	1	2	3	4
15	I consider how best to carry out a decision.	0	1	2	3	4
16	When making decisions I like to collect a lot of information.	0	1	2	3	4
17	I try to be clear about my objectives before choosing how to do a job.	0	1	2	3	4
18	I take a lot of care before choosing how to do a job.	0	1	2	3	4

Section 3: Communication Section

	Thinking of your facility generally:	Very Dissatisfied	Dissatisfied	Hard to say	Satisfied	Very Satisfied
19	Are you satisfied or dissatisfied with communication and the availability of information in your organization?	0	1	2	3	4

	How much information about your work do you get now from:	Very Little	Little	Hard to say	Much	Very Much
20	Your Supervisor	0	1	2	3	4
21	Fellow employees	0	1	2	3	4
22	Staff meetings	0	1	2	3	4
23	Memos, procedures and reports	0	1	2	3	4
24	Vendors	0	1	2	3	4
25	Computer based information systems (SAP, Virtual Bookshelf)	0	1	2	3	4

	What is the amount of information you receive now about the following job items?	Very Little	Little	Hard to say	Much	Very Much
26	My own work	0	1	2	3	4
27	Changes in production	0	1	2	3	4
28	Training and courses	0	1	2	3	4
29	Organisational changes	0	1	2	3	4
30	Changes in procedures / New Procedures	0	1	2	3	4

Section 4: Please write any comments you have on what helps or gets in the way of maintenance work at [the company]:

____

____

____

____

____

That is all! You have successfully completed the survey.
Thanks for taking the time to participate, and helping to make a better workplace. Please send the filled-in questionnaire to:
Ari Antonovsky, Mail drop WP 03-12L.

Appendix G – Factor Analysis of the *Design & Maintenance* scale

Four parameters were calculated using SPSS to assess the suitability of the data for Factor Analysis of the *Design & Maintenance* scale. Normality of the data was initially determined using the Shapiro-Wilk statistic, but all items returned a significant value, nominally indicating that the data violated the assumption of normality. However further tests of normality (Allen & Bennett, 2008) indicated the shape of histograms were approximately normal. Furthermore, the skewness and kurtosis data (Table 22) for scale items indicated approximately normal distributions, i.e., skewness and kurtosis statistics were between -1 and +1.

Table 22. Item statistics indicating normality of distributions.

Item No.	1	2	3	4	5	6	7	8
Skewness	.049	-.129	.076	.102	-.123	-.055	-.093	-.682
Kurtosis	-.24	-.144	-.339	.374	.001	-.108	-.345	1.019

Howell (2004) recommends that predictors that are highly correlated should not be used in Factor Analysis. The highest inter-item correlation in this data was $r = .408$, indicating that multi-collinearity was acceptable for Factor Analysis. The assumption of linearity between items was tested by producing scatterplots for a sample of items. An example of a linear relationship between Question 1 and Question 8 is provided in Figure 20.

Bartlett's Test of Sphericity was significant, returning a value of 226 (df= 28, $p < .001$). This result indicated factorability, though this test is recommended for fewer than five cases per variable (Allen & Bennett, 2008). Kaiser-Meyer-Olkin's Measure of Sampling Adequacy was .781. Values greater than .6 are considered acceptable for Factor Analysis (Tabachnick & Fidell, 2007). As the skewness and kurtosis statistics are all within the range of -1 to +1, the data for the scales was considered normally distributed.

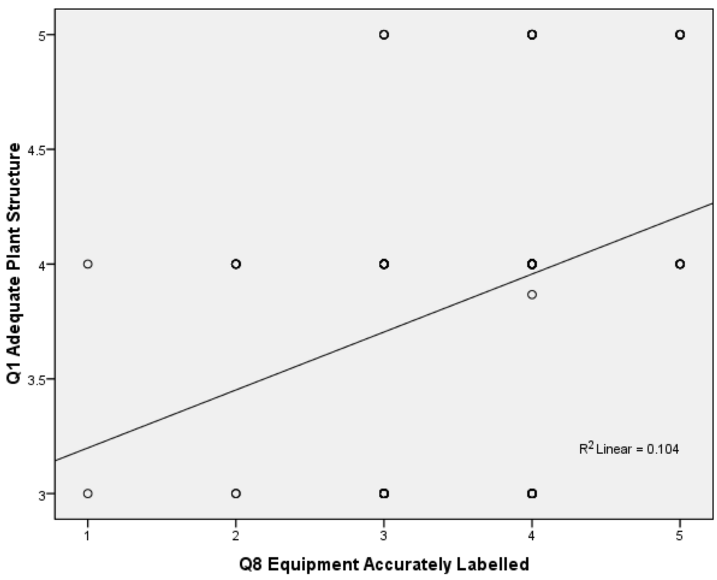

Figure 20. Scatterplot showing linear relationship between items in the *Design & Maintenance* scale.

Factor Analysis of the eight items in *Design & Maintenance* produced the Scree Plot of Eigenvalues shown in Figure 21. Two factors were found to have Eigenvalues greater than 1.0. The loadings for these factors are shown in Table 23. Cronbach's α resulting from the removal of each item is also listed. Internal reliability was found to decrease from the scale reliability (α=.729) if any item were to be removed. Therefore *Design & Maintenance* was kept as a single variable including all items in the original scale.

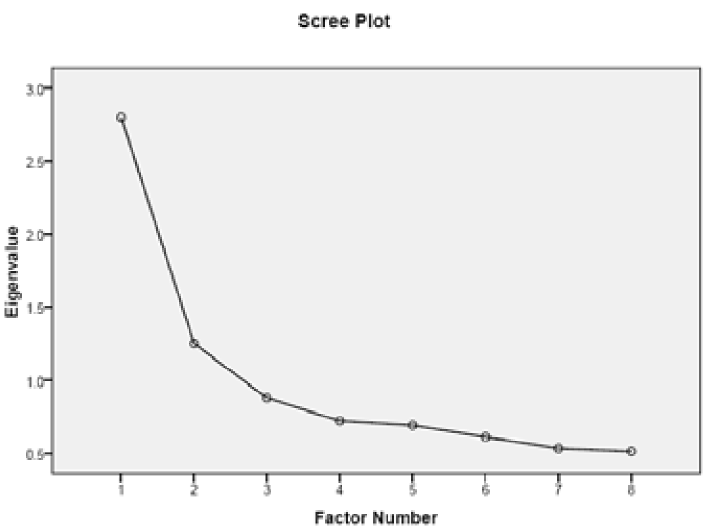

Figure 21. Eigenvalues for Factor Analysis of *Design & Maintenance* items.

Table 23. Factor loadings the items in the *Design & Maintenance* section of the survey.

Item	Factor 1	Factor 2	Cronbach's α if Item Deleted
Q1 Adequate Plant Structure	.526		.702
Q2 Adequate Parts, Spares and Materials	.478	.378	.684
Q3 Sufficient Access for Maintenance	.423	.393	.687
Q4 Maintenance or CM Overdue [a]		.644	.696
Q5 Problems with Modifications [a]		.651	.710
Q6 Problems with Non-standard Equipment [a]		.396	.709
Q7 Parts Installed Easily	.612		.718
Q8 Equipment Accurately Labelled	.541		.702

[a] **Reverse-coded**

Appendix H- Factor Analysis of the *Organisational Communication* items

For the *Organisational Communication* items, four parameters were calculated to assess the suitability of the data for Factor Analysis. Normality of the data was initially determined using the Shapiro-Wilk statistic, but here too all items returned a significant value. Further tests of normality (Allen & Bennett, 2008) indicated the shape of histograms were approximately normal. The skewness and kurtosis data (Table 24) for scale items indicated approximately normal distributions.

Table 24. Item statistics indicating normality of distributions.

Item No.	19	20	21	22	23	24	25	26	27	28	29	30
Skewness	-.332	-.562	-.566	-.168	-.631	.205	-.671	-.419	-.049	-.219	.045	-.035
Kurtosis	-.752	-.638	.680	-.835	-.207	-.587	-.223	-.306	-1.018	-.742	-.923	-.741

The assumption of linearity between items was tested by producing scatterplots for a sample of items in the *Organisational Communication* scale. An example of a linear relationship between Question 26 and Question 27 is provided in Figure 22. The highest inter-item correlation in this data was $r = .513$, indicating that multi-collinearity was acceptable for Factor Analysis.

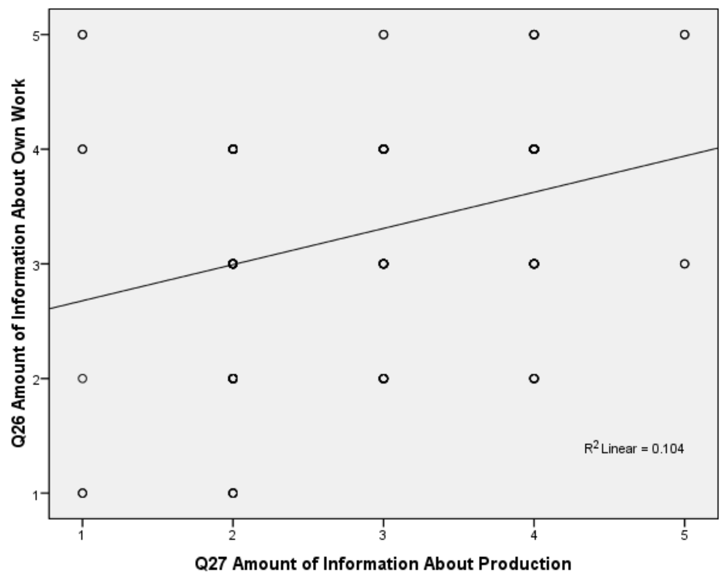

Figure 22. Scatterplot showing linear relationship between items in the *Organisational Communication* scale.

Bartlett's Test of Sphericity returned a value of 530(*df*= 66, *p*<.001), which indicated factorability. Kaiser-Meyer-Olkin's Measure of Sampling Adequacy was .804, also indicating factorability. As the skewness and kurtosis statistics were all within the range of -1 to +1, the data for the scales was considered normally distributed.

Factor Analysis of the 12 items in the *Organisational Communication* section produced the Scree Plot of Eigenvalues shown in Figure 23. Four factors were found to have Eigenvalues greater than 1.0. The loadings for these factors are shown in Table 25. The items loading on Factors 1 and 2 are relatively free of cross-loadings. Factor 3 cross-loads on a number of items while Factor four only has one item which does not cross load onto another factor. Therefore two factors were derived from the original OCD/2 scales included in the survey.

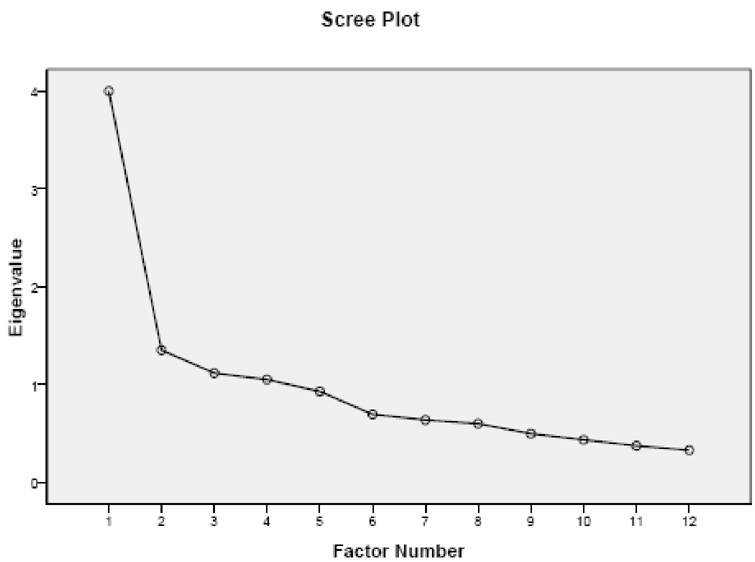

Figure 23. Eigenvalues for Factor Analysis of *Organisational Communication* items.

Table 25. Factor loadings for the items in the *Organisational Communication* section of the survey.

Item	Factor			
	1	2	3	4
Q19 Satisfied with Communication and Information	.443			
Q20 Information About Work From Supervisor	.809			
Q21 Information From Fellow Employees				
Q22 Information About Work From Staff Meetings	.502		.424	
Q23 Information From Procedures & Reports	.407		.517	.415
Q24 Information About Work From Vendors			.579	
Q25 Information From Computer Systems				.603
Q26 Amount of Information About Own Work	.633			
Q27 Amount of Information About Production		.613		
Q28 Amount of Information About Training		.475		
Q29 Amount of Information About Organisation		.534		
Q30 Amount of Information About New Procedures		.679		

Appendix I – Assumption Tests for ANOVAs and ANCOVAs

To determine the suitability of the collected data for analysis of variance and covariance, Shapiro-Wilk Tests for normality and Levene's Tests for the homogeneity of variance were conducted (Table 26 and 27).

Table 26. Tests for the suitability of analysis of variance for one-way ANOVA.

	Levene's Test		Reliability Ranking	Shapiro-Wilk		
Variable Name	*F*(2,50)	*p*		Statistic	df	*p*
Design & Maintenance	2.182	.123	Highest	.840	11	.031
			Middle	.926	21	.112
			Lowest	.961	21	.534
Vigilance	.048	.954	Highest	.948	11	.613
			Middle	.966	21	.638
			Lowest	.932	21	.152
Job-related feedback	2.010	.145	Highest	.939	11	.513
			Middle	.967	21	.662
			Lowest	.938	21	.201
Problem-solving	1.369	.264	Highest	.894	11	.158
			Middle	.953	21	.380
			Lowest	.959	21	.503
Information about change	2.624	.082	Highest	.926	11	.375
			Middle	.924	21	.104

The assumption of homogeneity was only violated for the items relating to *Information about change*. Allen and Bennett (2008) do not consider this a concern when groups are equal in size and are moderately large. The assumption of normality appeared to be violated for several variables, in which the Shapiro-Wilk Test returned a significant statistic ($p<.05$). They recommend a further test of normality by examining the skewness and kurtosis of the distribution. In all of these distributions, the skewness and kurtosis statistics were acceptable i.e., between -1 and +1.

Table 27. Tests for the suitability of analysis of variance for two-way ANOVA.

	Levene's Test		Shapiro-Wilk Test		
Variable Name	*F*(3,82)	*p*	Reliability	*F*(3,43)	*p*
Design & Maintenance	1.604	.195	Lower	.971	.333
			Higher	.960	.137
Vigilance	.234	.873	Lower	.926	.009
			Higher	.948	.049
Job-related feedback	1.567	.204	Lower	.951	.066
			Higher	.968	.266
Problem-solving	.253	.859	Lower	.956	.098
			Higher	.978	.583
Information about change	2.760	.047	Lower	.974	.439
			Higher	.975	.474

For the ANCOVAs, the co-variates must be normally distributed as well. Shapiro-Wilk Tests for the co-variates *Time at Facility* and *Employer* were significant, indicating a violation of the Assumption of Normality. However, histograms, and skewness and kurtosis statistics indicated that the data was approximately normally distributed. A further assumption in the suitability of data for ANCOVA is the homogeneity of regression slopes. The results (Table 28) indicated that the assumption of homogeneity of regression slopes was only violated for the interaction between *Reliability Level* and *Time at Facility* in the one-way analysis of *Design & Maintenance*.

Table 28. Tests for homogeneity of regression slopes.

Scale	Interaction Term		*F*	*p*
Design & Maintenance	*Reliability * Time at Facility*			
	One-way data	(2,47)	5.104	.010
	Two-way data	(1,79)	.104	.748
Job-related feedback	*Reliability * Employer*			
	One-way data	(1,45)	1.670	.203
	Two-way data	(1,77)	.618	.434

Finally, checking for linearity of the items within a scale was required. Scatterplots comparing the DVs with the co-variates were used to assess linearity of data. A scatterplot showing linearity of *Design & Maintenance* against *Time at Facility* is shown in Figure 24, and a scatterplot of *Job-related feedback* against *Employer* is shown in Figure 25.

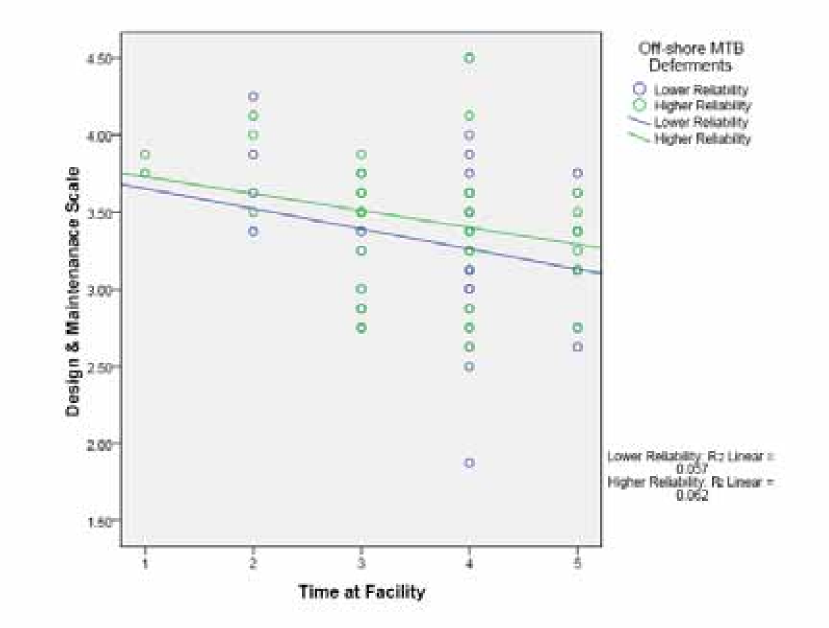

Figure 24. Scatterplot of *Design & Maintenance* against *Time at Facility.*

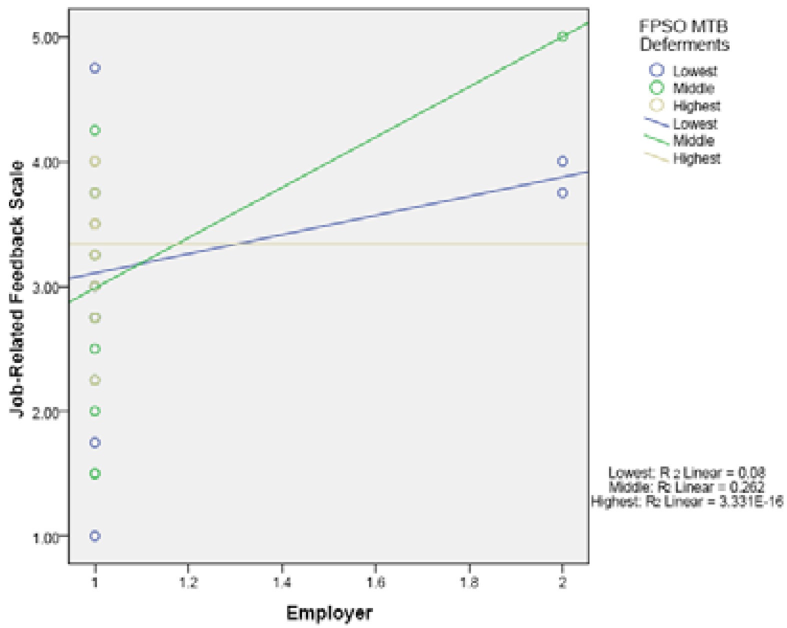

Figure 25. Scatterplot of *Job-related feedback* against *Employer.*