RELIABILITY ANALYSIS OF MARINE PILOTS USING ADVANCED DECISION MAKING METHODS

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Abstract

Seaports play a significant role in global logistics networks, contributing to the efficiency of both national and international economic growth. Dramatic changes in the supply chain encourage ports to maintain effective integration when delivering services. Ports are thus parts of complex systems operating in uncertain operational environments. Accident investigation shows that there has been a significant increase in marine accidents contributed to by human error during marine pilotage operations. The human element has been identified as a major critical factor for most operational failures. Therefore, an adequate understanding of the key factors influencing pilot reliability plays a vital role in all high-risk industries, among which maritime operations are included.

This study aims to develop a new quantitative marine pilot reliability assessment methodology, known as the Marine Pilot's Reliability Index (MPRI). The MPRI seeks to help decision makers in identifying the effects of certain factors on pilot reliability. Although human reliability has been investigated in different disciplines, there is no consensus on the selected criteria. Therefore, in this study, the researcher employed a hybrid research approach, comprised of qualitative and quantitative approaches in a sequential exploratory approach to elicit the key factors that are considered dominant in maintaining the reliability of a marine port pilot. This was conducted through a series of investigation tools such as field observation, semi-structured focus-group interviews, and port pilotage accident data analysis. This step culminated in a composite of four main criteria with thirteen sub-factors, which pilots considered dominant to their reliability. These factors are arranged in a hierarchal order forming the new developed MPRI.

To ensure the applicability of the identified MPRI factors, the researcher applied a Delphi technique in examining the degree of agreement among experts towards the identified MPRIs. Two rounds of questionnaires were conducted. The results obtained show a high degree of agreement among experts towards the identified factors. This is followed by the application of the analytical hierarchal process (AHP) approach to determine the relative weights of all identified criteria.

The second approach, a new conceptual MPRI interdependency model is constructed using a hybrid approach of a fuzzy decision-making trial and evaluation laboratory (FDEMATEL) and an analytical network process (ANP). This hybrid approach helps to deal with inherent uncertainties and highlights the degree of interdependences in the developed MPRIs.

To examine the feasibility of the proposed model and determine the outputs from this research, the researcher employed a fuzzy evidential reasoning (FER) for solving multiple criteria decision-making (MCDM) problems in conjunction with the aforementioned approaches to empirically assess the reliability of a marine pilot. The application of FER helps manage uncertainties resulting from the nature of operations. Three senior marine pilots have been assessed using the developed reliability assessment tool. The results reveal the novelty of this assessment tool in offering an effective and flexible reliability assessment and a diagnostic instrument for decision makers to predict a reduction in a pilot’s reliability. The developed model is partially validated using a sensitivity analysis. The novelty of this work offers a foundation towards assessing the reliability of marine pilotage operations using risk-based methodologies with variance techniques to facilitate the acquisition of qualitative and quantitative data and to ensure safe and efficient port operations.

Acknowledgement

I would like to take this opportunity to offer my gratitude to those who have contributed towards the success of this work.

The rewards of this work go first to my beloved daughters, Talah and Leena. When I wrote these words, I felt their happiness to surround me for the first time in a long while. I felt upset many times during this work due to a variety of challenges, but when I remembered their future and happiness, it encouraged me to work hard. I owe the success of this work to them, my SWEET HEARTS, first.

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I would also like to give special thanks to my parents and siblings for their encouragement, love, support, and prayers – especially my mother, who always prays for my success.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

ABS	American Bureau of Shipping
AHP	Analytical Hierarchy Process
AIS	Automatic Identification System
ANP	Analytical Network Process
ATHENA	A Technique for Human Error Analysis
Aver.	Average
BS	Body Strength
CI	Consistency Index
CL	Competence and Licensing
CR	Consistency Ratio
CREAM	Cognitive Reliability and Error Analysis Method
CRM	Crew Resource Management
CS	Communication Skills
DANP	DEMATEL-based Analytical Network Process
DEMATEL	Decision Making Trial and Evaluation Laboratory
DfT	Department for Transport
DM	Decision Making
DoB	Degrees of Belief
DT	Delphi Technique
ER	Evidential Reasoning
ETA	Estimated Time of Arrival
FDEMATEL	Fuzzy Decision Making Trial and Evaluation Laboratory
FER	Fuzzy Evidential Reasoning
FL	Fuzzy Logic
FMEA	Failures in a failure mode and effect analysis
FRBN	Fuzzy rule-based Bayesian Network
FST	Fuzzy set theory
FTOPSIS	Fuzzy Technique for Order Preference by Similarity to Ideal Solution
F&S	Fitness and Strength
GB	Global Weight
GRT	Gross Registered Tonnage

HEART	Human Error Assessment and Reduction Technique
HDMCDM	Hybrid Dynamic Multiple Criteria Decision Making
HI	Health Issues
HM	Harbour Master
HRA	Human Reliability Analysis
HR	Human Reliability
IAPH	International Association of Ports and Harbours
IDS	Intelligent Decision System
IMO	International Maritime Organisation
IMPA	International Association of Ports and Harbours
INRM	Influential Network Relation Map
IQR	Inter-Quartile Range
ISM	International Safety Management
JO	Jetty Operator
LW	Local Weight
MAIB	Marine Accident Investigation Branch
MCDM	Multi-Criteria Decision-Making
MCGA	Maritime Coast Guard Agency
Med	Median
MP	Marine Pilot
MPPOs	Marine Port Pilotage Operations
MPRI	Marine Pilots Reliability Index
MSC	Maritime Safety Committee
NASA	National Aeronautics and Space Administration
NTS	Non-Technical Skills
NUMAST	National Union of Marine Aviation and Shipping Transport
NW	Normalised Weight
OA	Operator Age
OF	Operator Fatigue
OS	Operational Stress
OTP	Operator Technical Proficiency
PE	Pilotage Experience
PF	Personal Fatigue
PH	Personal Health

Ph&MS	Physical and Mental Strength
PIS	Participant Information Sheet
PMSC	Port Marine Safety Code
POD	Port Operational Department
PRI	Pilot’s Reliability Index
PS	Pilot Station
PSC	Port State Control
QPL	Qualification and Pilotage Licensing
RI	Random Index
SA	Situational Awareness
SM	Ship Master
SMS	Safety Management System
SOD	Ship Operational Department
ST	Special Training
STCW	Standards of Training, Certification and Watch-keeping
TC	Training Courses
TFN	Triangular Fuzzy Numbers
TM	Tug Master
TP	Technical Proficiency
T&L	Teamwork & Leadership
VIKOR	VIsekriterijumsko KOmpromisno Rangiranje
VTS	Vessel Traffic Service
WH	Working Hours
WEx	Working Experience
WEnv	Working Environment
WS	Work Stresses

Chapter one: Introduction

1.1 Chapter summary

This chapter presents the background of the research and an explanation of the principal research objectives and sub-objectives, which have been developed through a broad and comprehensive literature review. The justification of the research study is also addressed in order to identify the importance of the study based on industrial needs. A number of techniques and methods are highlighted in brief for consideration. Finally, the structure and scope of this research are outlined.

1.2 Research background

Seaports are vital to global logistics networks and economic growth. Dramatic changes in the supply chain in terms of ship size and economical competition encourage ports to maintain optimal integration in the services they host (Robinson, 2002; Mangan et al., 2008; Song and Panayides, 2008). Ports are thus parts of complex systems operating in an uncertain operational environment. Accordingly, the interests of different port stakeholders are in conflict due to the presence of uncertainty in operations (Notteboom and Winkelmans, 2003). To ensure an efficient relationship with key port stakeholders and secure their allegiance, port managers have increasingly relied on maintaining proper management practices (Dooms and Verbeke, 2007).

In the literature, port performance measurement has been a point of interest for many scholars in the field over the past three decades (Ha et al., 2017). However, there is still a significant need for further investigation and industrial assessment to fill the gap in academic research on optimising port operational performance. Existing literature has focused on limited operational dimensions or specific areas of the port to measure performance. Furthermore, most of the identified factors affecting marine port operations – including pilotage services – are considered independently. It has been suggested that port systems be highlighted collectively rather than independently (Board, 1994). The justification for this is that when a broad range of options is considered, the implementation process is usually fragmented and uncoordinated due to the absence of proper correspondence between economic objectives and safety aspects within the port. Therefore, developing an effective quantitative reliability assessment tool for a marine port pilotage operation is complicated by a lack of cohesion and wide variation within marine navigation and piloting systems. These variations occur in terms of port, waterway and working environments, vessel types, equipment used, operating characteristics, and professional qualifications. The interactions among these factors result in safety problems that defy a simple solution.

Enhancing the safety of marine port pilotage operations requires a careful consideration of risks associated with such operations. One of the factors most commonly identified by scholars in measuring port performance is the human element, i.e., the human influence on operations (Zhang et al., 2013; John et al., 2014).

The human element has been identified as a major critical factor in most operational failures (Barnett et al., 2006; Yee et al., 2005; Riahi, et al., 2013). The marine port pilotage operation is known as a complex and interdependent process in a large sociotechnical system that encompasses massive complex interactions between humans and equipment. Moreover, the pilotage operation is extremely reliant on human performance and is therefore subject to considerable diversity with great variability in operational conditions. Human error has been the cause of between 80 and 96 per cent of incidents with serious consequences reported by high-risk industries such as aviation, nuclear, maritime, and health care (O’Connor et al., 2002; Embrey, 1993; Reason, 1990; Kariuki and Lowe, 2007) (see chapter 2). It is essential to understand the influence of key factors on human reliability in high-risk industries, and the marine and maritime industry is no exception.

Operational safety has improved over the last several decades, yet other safety issues have been raised which suggest a need for further safety resolutions. Despite efforts to enhance marine safety, major shipping accidents continue to occur, and these accidents have occurred mainly during the ship/port interface (Hsu, 2012) under the guidance of a common human element: the marine pilot. Seaports have become the subject of worldwide attention, as handling different types and sizes of ships requires a high level of safety during a pilotage operation. Given the complexity of maritime operations during ship/port handling, marine pilots have a significant role in safe handling procedures (Douglas et al., 1997).

This research investigates the difficulties associated with human reliability assessment, especially in marine port pilotage operations (MPPOs). The research attempts to develop a novel quantitative marine pilotage reliability index (MPRIs) to enable port safety officers to monitor, control, and mitigate the risks resulting from the degradation of pilotage operators' reliability. The questions this study raises to discover the significance of the topic include the following:

- What are the main contributory factors that constitute human reliability within MPPOs? Are they independent or interdependent?
- To what extent do these factors critically degrade MPPO?
- Will the implemented research framework help to proactively assess reliability?

1.3 Research aim and objectives

This research aims to develop a novel marine pilot reliability index (MPRIs) to assess the reliability of marine port pilotage operations. This research seeks to allow decision-makers to predict, mitigate, and implement operational procedures to enhance the reliability of MPPOs' to ensure higher operational safety. In order to accomplish this research aim, this study addresses the following main research objectives:

1- To comprehensively review previous efforts to monitor human reliability across different disciplines – including maritime operations – to highlight the risks associated with reliability degradation and identify the research gap that needs to be filled.

2- To identify and analyse the key factors that shape marine pilot reliability based on the current operational practices to build a rational index that is capable of being used by decision makers, especially within MPPOs.

3- To examine the degree of consensus among experts on the selected factors and highlight the degree of importance of each criterion towards shaping the reliability of marine pilots.

4- To develop an effective method to analyse the degree of interactions among the identified factors to enable decision makers to predict the possibility of reliability fluctuations.

5- To develop an effective systematic quantitative human reliability measurement tool to allow decision makers to improve the overall reliability of MPPOs.

6- To conduct a real case study in one of selected marine port to assess the reliability of a marine port pilot and test the validity of the proposed model.

The achievement of the highlighted objectives are outlined across chapters 2, 3, 4, 5, and 6 (see Figure 1.1).

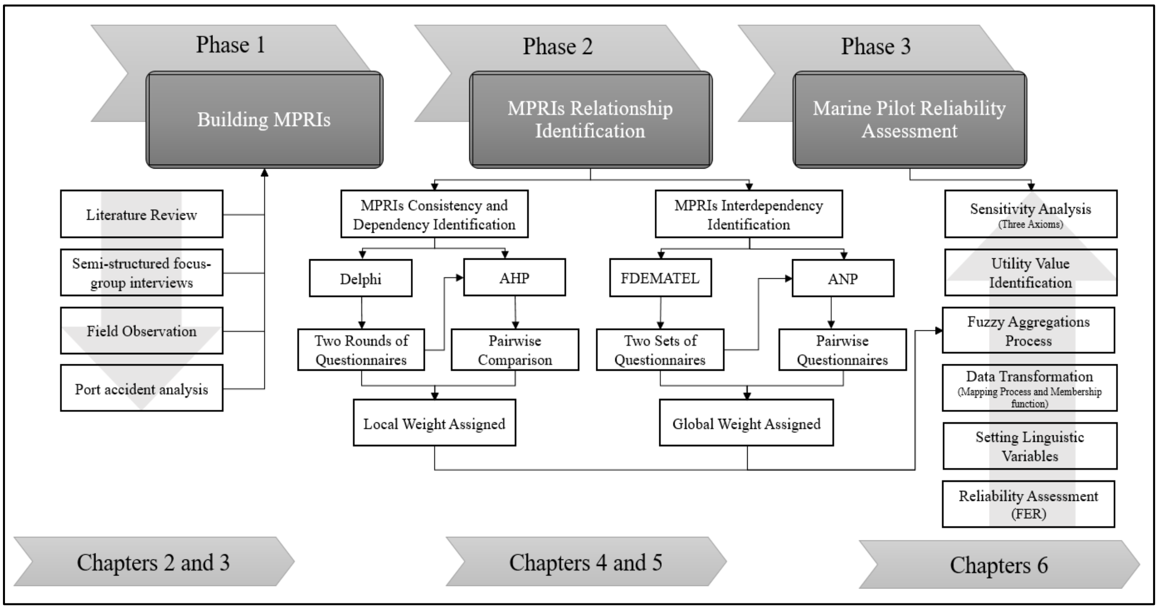

Figure 1.1. Reliability assessment framework

The first objective is addressed within chapter two. The development of the MPRIs is achieved through a field investigation to understand the current operational working practices and qualitative elucidation of more in-depth information from experts about their concerns. This is illustrated in chapter 3. The degree of consensus among experts was examined holistically. Newly developed reliability shaping factors were examined by two rounds of Delphi surveys. This was followed by ranking the degree of importance using the AHP method, and this is featured in chapter 4. Moreover, the identified factors were believed to be interdependent. Therefore, they were examined using the fuzzy decision-making trial and evaluation laboratory (FDEMATEL) to identify the cause and effect factors. This was followed by identifying the global weight using analytical network process (ANP), and this is illustrated in chapter 5. Finally, featured in chapter 6, a marine pilot reliability assessment was conducted using a fuzzy evidential reasoning (FER) in conjunction with the aforementioned approaches through assessing three senior marine pilots empirically in a major marine port to examine the effectiveness of the developed MPRI.

1.4 Structure of Thesis

This research is outlined through seven chapters, as shown in Figure 1.2.

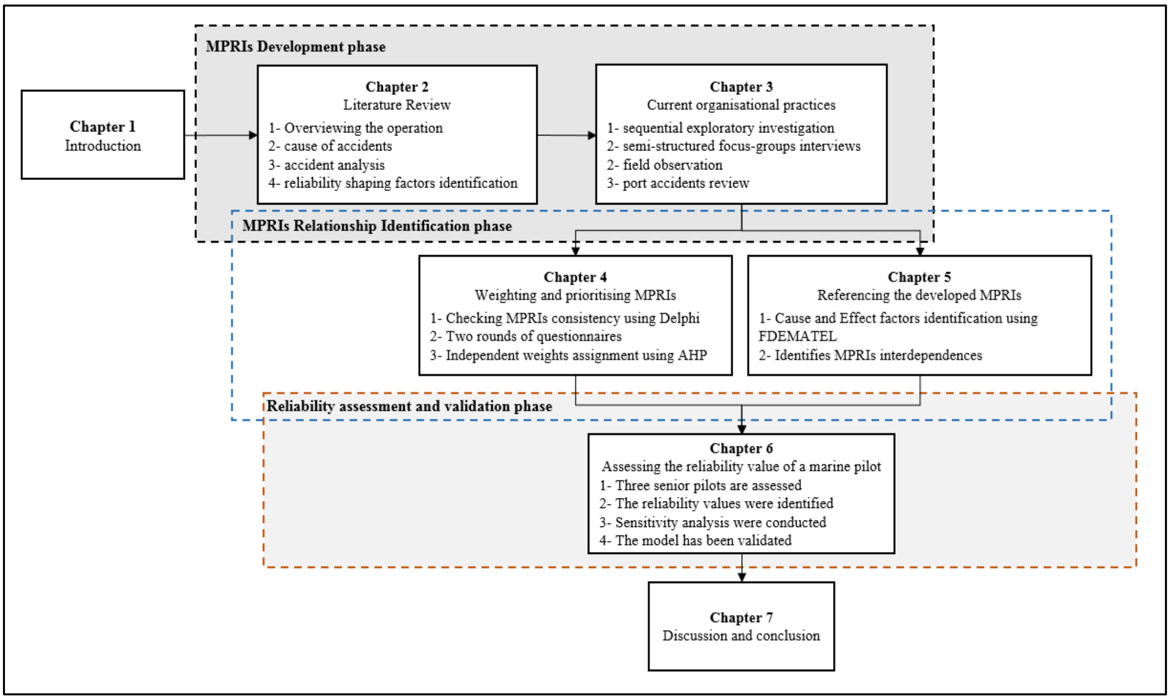

Figure 1.2. Thesis outlines

These chapters are briefly described as follows:

Chapter 1 This chapter begins with the initiatives of this research. The research aim and objectives were highlighted followed by an explanation of the importance and justification of conducting this research. Finally, the chapter provides brief descriptions for each process conducted in the study to outline the research process.

Chapter 2 This chapter presents the current literature related to the maritime industry, aiming to highlight the current research conducted in port and operational performance. It also seeks to identify the current research gap that needs to be filled. In addition, this chapter gives an overview of other research, which assessed human performance in order to build an overview on the current investigated factors. Several relevant books, journals, conference papers, tutorials, and reports are reviewed to build an effective approach towards developing the research model. This chapter provides an essential picture of different perspectives towards the human element and the way it can be assessed. Finally, this chapter contributes significantly towards developing the survey and identifying the analysis tools required to achieve the aim of this research.

Chapter 3 A field investigation was conducted for the purpose of this chapter in a major marine port to highlight the current organisational working practices in the maritime industry. This chapter aims to develop and examine the effectiveness and the suitability of the identified factors highlighted across different industries within marine port pilotage operations. Qualitative sequential exploratory research paradigms were used via employing field observation, semi-structured focus-grouped interviews, and port accidents data analysis in order to justify the factors which shape reliability. The proposed research MPRIs were developed as a result of this chapter.

Chapter 4 The developed MPRIs from the previous chapter are tested in this chapter in terms of expert agreement on the selected criteria. Two rounds of questionnaires follow the main features of the Delphi technique to obtain the most desired factors. Following the confirmation process from the second round, a pairwise comparison based on the AHP approach was conducted to highlight the degree of importance given to each local criterion on the developed model. The significance of this step is to highlight the degree of influence that factors play in shaping operator reliability.

Chapter 5 In this chapter, and following the discussion within the conducted interviews, it is considered crucial to highlight the degree of interdependencies among the identified factors. The links between factors are observed, which necessitate the use of a more suitable approach that is capable of discovering the degree of influence between factors. Therefore, a proposed FDEMATEL approach aims to highlight the cause and effect factors that significantly provoke fluctuations in overall reliability. The identified factors were then tested by a non-linear pairwise comparison employing the ANP approach to identify the degree of influence among criteria within the MPRIs. As a result of the work explained in this chapter, the global weight of each identified MPRI was found.

Chapter 6 This chapter examines the feasibility of the proposed MPRIs by assessing the reliability of three senior marine port pilots with considerable pilotage working experience within the port industry. The empirical investigation took place in a major port, employing the results obtained from chapters 3, 4, and 5 in conjunction with the application of the fuzzy evidential reasoning (FER) approach. The developed model was then tested using a sensitivity analysis. The chapter concludes with the suitability of the proposed model in assessing the reliability of a marine port pilot, which therefore achieves the aim of this research.

Chapter 7 This chapter describes the overall observations and the results obtained from all chapters. This chapter also highlights the drawbacks and challenges faced during this investigation. The research contributions are explained in detail, and recommendations are provided on considerations for further future investigations.

The references and appendices, which include some essential data that cannot be included within the chapter, are featured after chapter 7.

Chapter Two: Literature review

2.1 Chapter summary

This chapter reviews the current literature related to the objective of this research. An overview of the significant marine pilotage operations is followed by an identification of the main cause of marine accidents. Historical data for marine failures is highlighted to show the significant need to enhance the reliability of marine operators. This is followed by overviewing other industrial efforts to develop the reliability of operators in order to develop a marine pilot reliability index.

2.2 Introduction

During the century preceding this research, the world’s economy grew significantly, and 80 per cent of the world’s goods by volume are transported by sea through ports. This increase has seen a subsequent increase in marine accidents within the last century, and accident investigations show that these accidents mainly occur within the confines of the seaport (Oltedal and McArthur, 2011; Bukhari et al., 2013). A total of 1,383 merchant shipping accidents occurred within UK port areas between 2001 and 2011, where human error constitutes 51 per cent of the total number of accidents that occurred during that time (MAIB, 2016). Thus, seaports have become the subject of increasing attention in the UK and worldwide, as handling different types and sizes of ships requires a high level of safety during pilotage operations. However, with the complexity of the maritime operations during ship/port handling, marine pilots make a significant contribution to safe handling procedures (Douglas et al., 1997). The main role of marine pilots is to ensure a vessel’s safety while navigating within a port’s limits in compliance with local regulations and to protect the port’s facilities, trade, and environment (Darbra et al., 2007). Therefore, the maritime industry, as any high-risk industry, is driven by the human element (Rothblum, 2000). Thus, accidents are mostly caused by human errors (Riahi et al., 2012).

According to DNV (2002), humans are the main cause of most maritime accidents. Human error constitutes 80-96 per cent of reported accidents in most critical industries (Barnett et al., 2006; Yee et al., 2005; Riahi, et al., 2013; O'Connor et al., 2002; Embrey, 1993; Reason, 1990; Kariuki and Lowe, 2007; Ren et al., 2008; Helmreich et al., 1999). According to Hollnagel and Amalberti (2001), the term 'human error' has different meanings, including human error as a cause, as an event, and as a consequence. Reason (1990) attempted to stipulate a generic term for human error as the failure of a planned sequence of mental or physical activities to accomplish its planned outcome when this failure cannot be attributed to the involvement of organisational assistance. He added that the problem of human error can be divided into two different approaches: personal and organisational. The personal approach is linked to individual errors, whereas the organisational approach is linked to the surrounding environment in which the operator works (Reason, 2000). Errors caused by humans can be the result of operational failure, poor management, and deficiency in scheduled maintenance or system design (Chauvin et al., 2013). Human error could be the result of an accumulated latent management failure over time left without proper action. For this reason, researchers interested in human reliability analysis (HRA) use the term 'human failure event' rather than generalising it into human error. This is done to avoid implications that result from blame during incident or accident investigations.

Human reliability (HR) varies both in its definition and in the way it can be assessed. According to Swain and Guttmann (1983), HR is known as the probability of an operator to perform actions in accordance with a system's demand and plan without conducting any unnecessary actions that can impact overall operational performance. Studies show that personal issues can influence human performance and behaviour, which leads to marine accidents or incidents (Ramin, 2010). Moreover, as mentioned above, any tool that helps to assess HR is called human reliability analysis (HRA) (Swain, 1990). HRA is helpful in risk assessment, as it uses methods derived from engineering systems and human psychology to highlight the degree of human contribution to a risk. Therefore, HRA includes a number of methods aiming to trace the causation of a human failure and to evaluate the likelihood of its occurrence (Pyy, 2000).

Accordingly, this study aims to develop an assessment tool with the capacity to assess the reliability of marine pilots during pilotage operations, which is achieved by investigating empirical data on existing pilotage practices. The following section presents an overview of port pilotage operations, which is followed by a section that presents historical failure data and a statistical analysis. The section also highlights the causes of marine accidents and pilotage hazards. The paper then presents an overview of the current efforts and progression of the HRA. Finally, a highlight of the factors that shape human performance across different industries is presented.

2.3 Port pilotage operations

Ships have been guided by marine pilots with local knowledge for centuries when entering or leaving ports. The significant role that pilots play has been recognised by the International Maritime Organisation (IMO) since 1968, when it adopted the assembly resolution A.159 (ES.IV) ‘recommendation on pilotage’. The resolution stated that it is important to employ a qualified pilot in a port’s approaches and other port areas where local knowledge of the port, language, and regulations is required (IMO, 2016). This resolution recommends that the port authority controlling pilotage operations must provide a high standard of pilotage service by defining the most appropriate safety measures, ships, and classes of ships that are mandatory to be piloted by an official designated pilot (IMO, 2016).

A pilot with local knowledge is an expert in the area, able to recognise hazards to navigation and establish an effective method of communication with shore authorities and tugs using local language, especially when a shipmaster is unfamiliar with the area. Therefore, in 2003, the recommendations on training, certification, and operational procedures for maritime pilots other than deep-sea pilots were adopted by the IMO under the resolution A.960 (23). Through this resolution, the IMO highlighted the significant role that pilots play in promoting maritime safety and protecting the environment. However, the degree of influence of other players involved in pilotage operations – such as shipmasters, tug masters, harbour masters, and VTS operators – is out of the scope of this study, and requires further investigation. Moreover, the IMO is not willing to become involved in setting pilots' certification standards or licencing, because each pilotage area requires highly specialised experience and local knowledge on the part of the pilot (Board, 1994; IMPA, 2004). Therefore, port authorities have both statutory and non-statutory powers, which allow a port authority to state the minimum requirements and qualifications needed to assign a designated person to safely berth and un-berth ships calling at that port (IMPA, 2004).

In the United Kingdom, the Port Marine Safety Code (PMSC) is the code that, according to the Department for Transport (DfT) (2015, p. 6), refers to 'some of existing legal duties and powers that affect harbour authorities in relation to marine safety, but it does not – in itself – create any new legal duties for harbour authorities'. This code was proposed mainly for a designated person who is responsible for the safety of marine operations in her/his waters and approaches, who is called the 'duty holder' or 'harbour board'. The role of harbour board members is to regard themselves, either individually or collectively, responsible for maintaining the code's standards through the following procedures (PMSC, 2015, p. 8):

1- Review and be aware of their existing powers based on local and national legislation;
2- Comply with the duties and powers under existing legislation, as appropriate;

3- Ensure all risks are formally assessed and as low as reasonably practicable in accordance with good practice;
4- Operate an effective marine safety management system (SMS) which has been developed after consultation and uses formal risk assessment;
5- Use competent people (i.e. trained, qualified, and experienced) in positions of responsibility for navigation safety;
6- Monitor, review and audit the marine SMS on a regular basis – an independent designated person has a key role in providing assurance for the duty holder;
7- Publish a safety plan showing how the standard in the Code will be met and a report assessing the performance against the plan; and
8- Comply with directions from the General Lighthouse Authorities and supply information & returns as required.

In addition, harbour authorities should seek additional powers if the existing powers are insufficient to meet their obligations to provide safe navigation and mitigate hazards that cause maritime accidents within pilotage and port operations.

2.4 Historical failure data and statistical analysis

A historical analysis of the accidents that have occurred helps to identify the main causes that lead to the most frequent accidents within a port's jurisdiction, their origins, and their consequences. The analysis helps to identify risks that affect the reliability of the organisation by underlining useful information for a decision maker to implement safer operating procedures along with required contingency plans. Therefore, two sets of data have been obtained through direct contact with a UK Maritime Accident Investigation Branch (MAIB) to obtain in-depth accident details. Contact was also made through their website for general information and statistics. The reason for this is because the data set obtained from them directly covered the period between 2001 and 2011, and it was last updated at the end of 2011. Meanwhile, the online sets gave the total number of accidents that occurred between 1998 and 2015 without further details.

The fluctuation over time of annual ship accidents and the number of accidents related to a person reported to the MAIB during a period of 18 years are represented in Figure 2.1. There were a total of 2,527 ship-related accidents, and 4,276 person-related accidents. Thus, person-related accidents represent the majority over the period. In 1998, this number was significantly high, reaching 330 accidents, which represents almost 8 per cent of the total number of reported accidents. By the end of the covered period, this number had declined by more than half – to 141 accidents – which represents 3.3 per cent of the total number of reported accidents. On the other hand, the number of accidents in relation to ships had declined in 2015 by half compared with the total number of reported accidents counted in 1998. The percentage of ship accidents in 1998 was 8.7%, while in 2015, it was only 4.7%. In general, this is still high, as the danger of accidents occurring has a significant impact on a country’s overall economy, port infrastructure, and human lives. Although it is apparent that the total number of accidents has progressively decreased, it has remained steady since 2013 at an average of 140 and 120 reported person and ship accidents respectively.

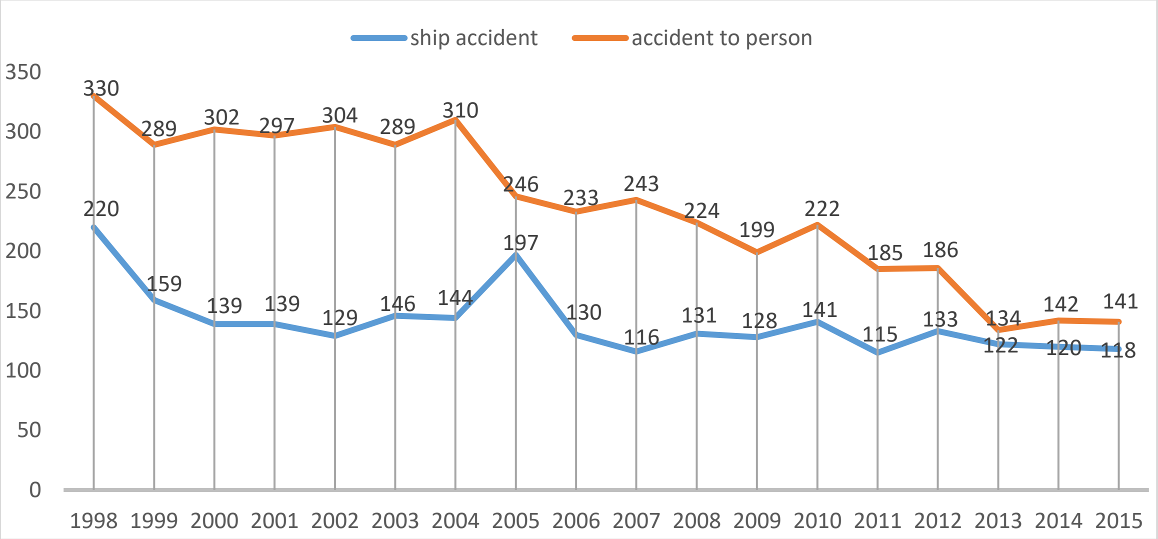

Figure 2.1. The number of ship accidents and person accidents for UK merchant vessels of ≥100 GRT (1998-2015) [MAIB, 2016]

This reduction may be due, but not limited to, the introduction of an organisational and industry-wide safety culture (Hsu, 2012), the evolution of container ships (Wang and Foinikis, 2001), and technological enhancement (John et al., 2014). These factors help to improve operational awareness and organisational safety aspects.

A restricted search obtained from the data given by the MAIB for the period between 2001 and 2011 resulted in a detailed accident record rather than a quantified number of accidents. This means that one accident can be found in several records, which requires considerable adjustment to avoid statistical errors. However, the total number of accidents that occurred within UK waters over a decade starting from 2001 was found to be 1,383, 957, and 362 accidents within the port area, on passage and other type of accidents respectively (see Figure 2.2).

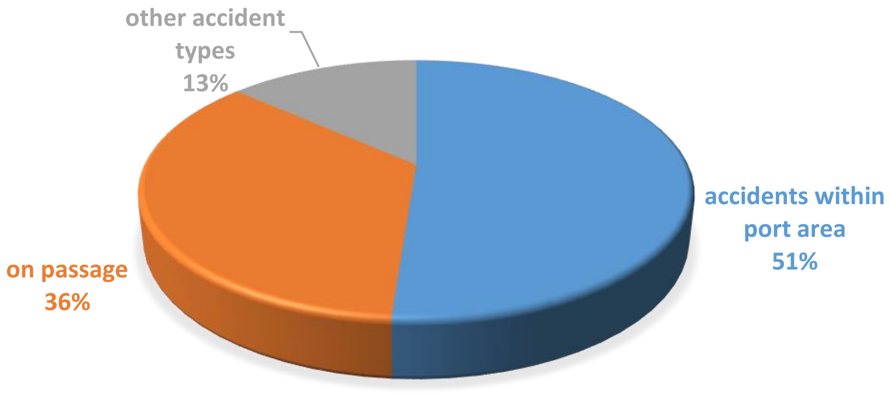

Figure 2.2. Merchant vessel accidents (≥500 GRT) within UK waters [source: original]

The percentage shown in Figure 2.2 confirms that ships approaching a confined body of water are subject to an increased level of risks (Darbra et al., 2007; Liu et al., 2005; Hsu, 2012). The probability of accidents occurring becomes higher due to increased traffic, shallow waters and the effect of hydrodynamic interactions, tidal effects, and technical difficulties during ship handling operations. Fifty-one per cent of accidents that occur within the port area are due to technical, human, or a combination of the two factors, which represents the majority of reported accidents within UK waters only. These accidents often occur due to a combination of accidental events of one, or a combination of more than one, operational component that it is essential for successful completion of the operation. A classification of the places where these accidents occurred is shown in Figure 2.3, covering a 10-year period within UK waters between 2001 and 2011 according to the MAIB (2016) reports. The following failures occurred: while at anchor (67), drifting (8), cargo loading and discharging (44), alongside or moored (343), during mooring operation (122), during entering or leaving the port (788), and during anchoring operation (11). The percentages for the different places can be seen in Figure 2.3.

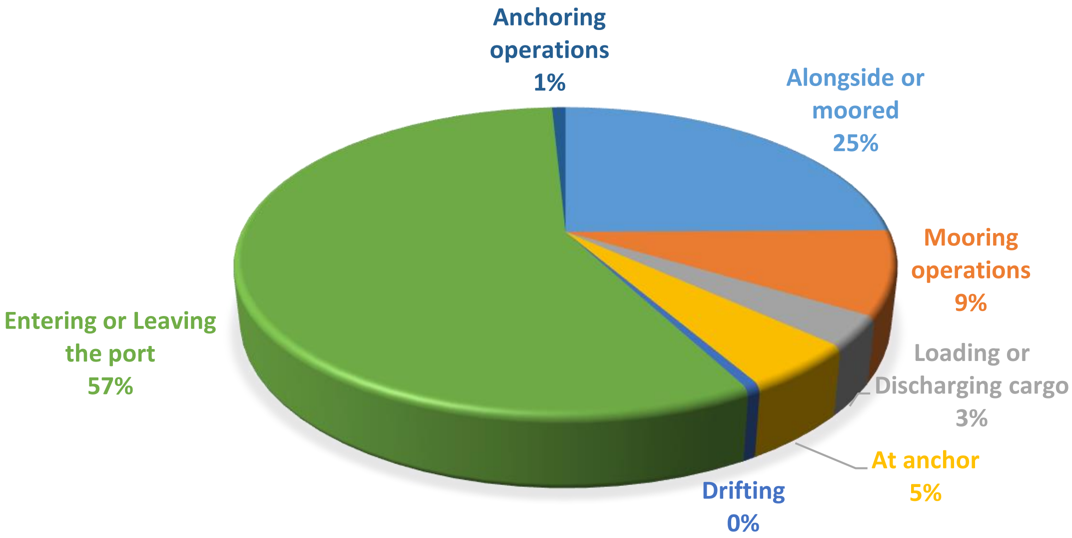

Figure 2.3. Merchant vessel accidents within UK port areas [source: original]

As shown in Figure 2.3, the majority of accidents take place while transiting in or out of the port (57 per cent/ 788 accidents of 1383). The second highest number of accidents occurs when the ship is placed alongside or moored to the jetty (25 per cent/ 343 of the total number of accidents). This finding resulted in the search being narrowed to identify the root cause of these accidents. Accordingly, Figure 2.4 shows the main causes of accidents. Four main factors were brought to light: the human factor (444 cases), technical factor (216 cases), a combination of these two (118 cases), and unknown factors (10 cases). It is therefore not surprising that the majority of accidents that occur during transiting in a port are due to human actions. This necessitates the development of a methodology that can optimise the reliability of pilotage operation within ports.

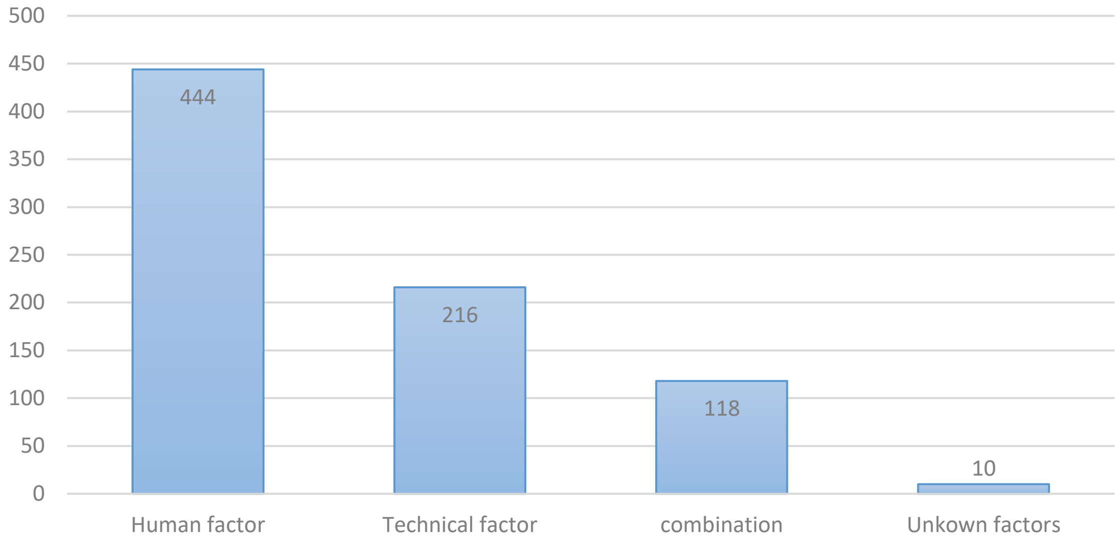

Figure 2.4. Cause of accidents during leaving or entering port (2001-2011) [source: original]

Furthermore, Figure 2.5 indicates where the accidents occurred when entering or leaving the port, namely within port/harbour area, river/canal, coastal waters, and non-tidal waters, with percentages of 61.8%, 16.9%, 20.9%, and 0.4 per cent respectively. The nature of the accidents is represented in Figure 2.6, which displays the total for each individual accident type.

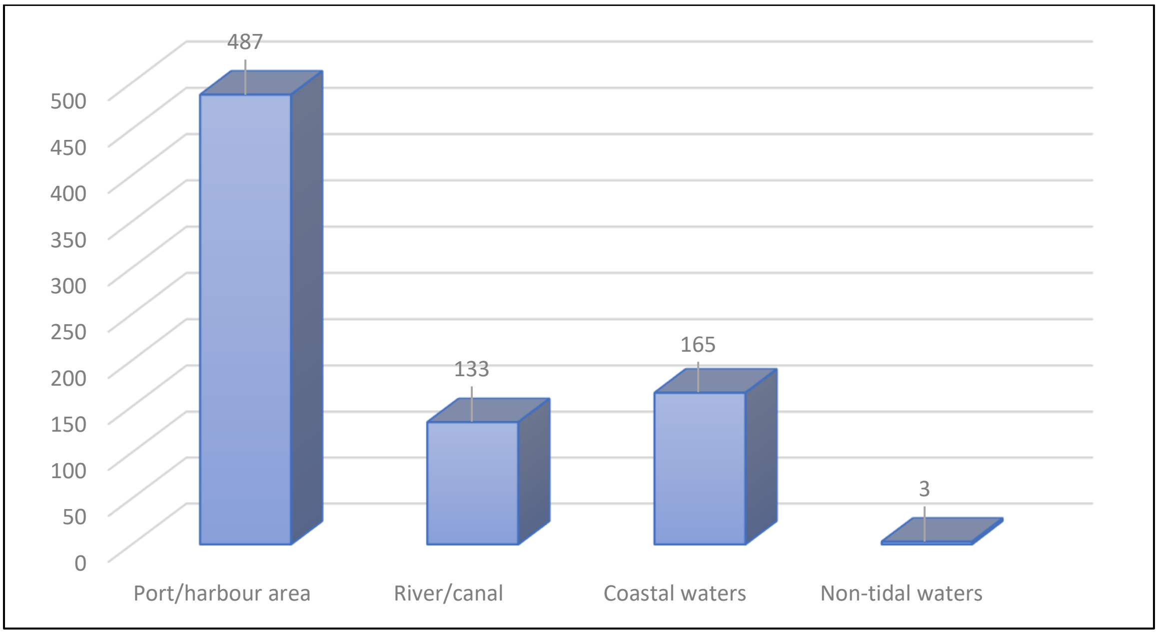

Figure 2.5. The number of accidents according to place when leaving or entering port [source: original]

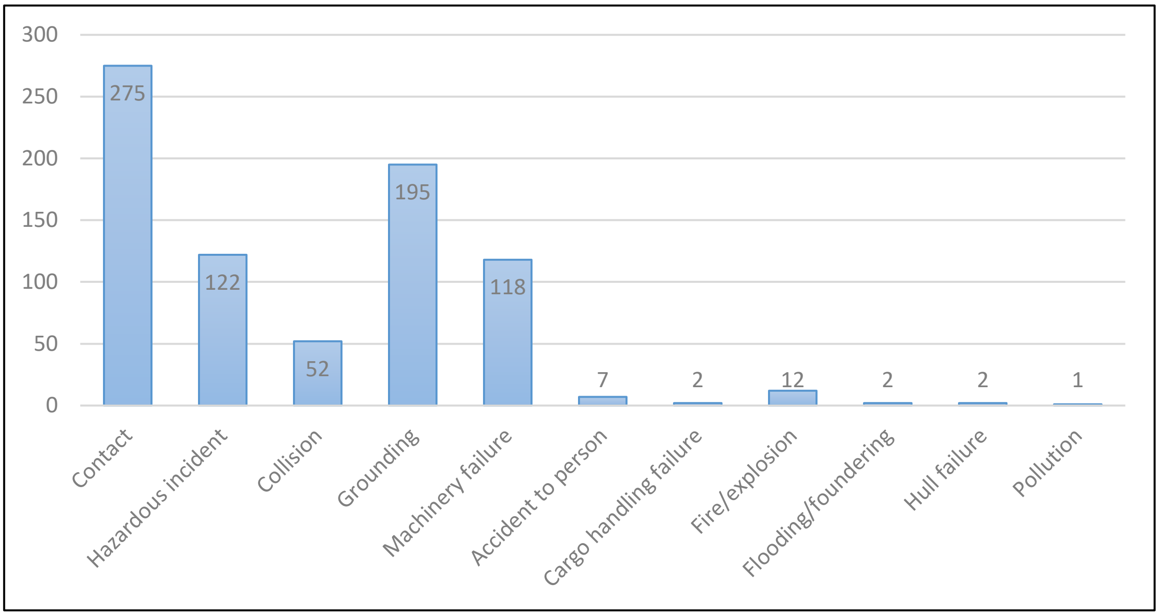

Figure 2.6. The nature of accidents when leaving or entering port [source: original]

2.5 Causes of marine accidents

The shipping industry is a profession characterised by a high rate of fatal injuries resulting from organisational accidents and maritime disasters (Hansenet al., 2002). It is similar to any other critical industry at risk, in that it is driven by the human element (Rothblum, 2000) where humans contribute in some way to about 80-96 per cent of reported maritime accidents. This study has used several maritime accident events for the purpose of risk model development. Analysing maritime accidents, as an effective tool for developing a risk model, can support risk development in a way which can provide operational alternatives and accident prevention.

The UK Marine Accident Investigation Branch (MAIB) declared that the human element still dominates the majority of maritime accidents (MAIB, 2016). Similar to other critical industries, according to Goulielmos et al., (2012), operational errors caused by a human element were identified as the second largest cause of losses in the chemical industry. The tendency of human beings to build in error results from operational errors such as distraction, stresses, and ineffective communication between workers were identified as the main causes of human failure across different disciplines (Board, 1994). On the other hand, the standard of management has been criticised by Turner (1994), as it does not prevent accidents. Thus, it is necessary to improve management characteristics by avoiding rigid beliefs, improving communication, and acknowledging potential consequences, as this will help, to some extent, to avoid unfavourable consequences.

In addition, data provided by New Zealand shows that 49 per cent of shipping accidents resulted from the human element, while 35 per cent were due to technical failure, and 16 per cent were caused by environmental factors (Hetherington et al., 2006). Since the accident details declared by the MAIB (2016) (see section 2.6) show that the main reasons behind the majority of marine accidents within ports were due to human error (57%), technical failure (27.76%), or a combination of these (15.17%), it therefore is essential to highlight the roots of causation that critically influence human performance.

It is worth mentioning that maritime operations are highly regulated, instructed, and internationally directed in stressing the importance of the human factor and an organisational safety culture (Berg, 2013). However, the establishment of an organisational safety culture does not overcome the serious barriers that obscure enhancements made to safety management. Therefore, it is essential to highlight how the organisational safety culture within the industry can critically influence human error.

2.5.1 Human error

Human error characterises the majority of accident cases (Barnett et al., 2006) and is adversely involved in about 80-96 per cent of reported accidents in most critical industries (Yee et al., 2005; Riahi et al., 2013; O’Connor et al., 2002; Embrey, 1990; Johnston et al., 2011). The most common human error causes have been linked to operator’s misjudgement, improper watch keeping, and not following the standard regulations.

Although Classification Societies came into existence in the 1760s, the IMO was established in 1948, and both are involved in enhancing maritime safety, there is still a high number of maritime accidents. However, the main focus of the IMO in the 1990s was the technical safety aspects of shipping. Since then, its emphasis has shifted towards factors aiming to improve the human element. This was followed by the IMO's introduction of International Safety Management (ISM) in 1998 (Goulielmos et al., 2012). According to O'Neil (2004), accident occurrences cannot be avoided through regulation implementation alone, as the enhancement of safety requires proper organisational maintenance and reliable operational practices.

Barnett et al. (2006) reviewed maritime accident databases from the United Kingdom, United States, Norway, and Canada, and they confirmed that human error was the main contributory factor within the maritime industry. This review illustrates that major maritime accidents are not caused by technical problems, but by failures of the crew to appropriately respond to the situation. They concluded that, although the number of accidents is declining, human error continues to be the dominant factor in 80 per cent to 85 per cent of all accidents.

In a study of 100 Dutch marine accidents, Rothblum (2000) identified that human error was involved in 96 of these accidents. In 93 per cent of these accidents, there were multiple human contributions by two or more operators. These operators were both dependent on and influenced by the action of the other. Nonetheless, they had limitations as human beings and differed in their ability to perform their work and duties accordingly (Rothblum, 2000). Consequently, operators at a port and their work features such as their technical skills and working environments may impact the safety of navigation within the port (Hsu, 2012).

Hetherington et al. (2006) stated that human factors have been identified as the reason for most accidents at sea. Worker fatigue, stresses, and health problems are the main observable factors that play vital roles in workers' performance degradation. Rasmussen et al. (2015) have highlighted that insufficient technical skills, insufficient mental abilities, and incompetence in mastering the language of communication as an additional set of operator performance-shaping factors. . In addition, they pointed to safety training, team management, and safety culture implementation as organisational factors which shape workers' performance.

Many critical areas have been addressed by the United States Coast Guard to enhance and improve human performance and safety (Rothblum, 2000). The most dominant factors are human fatigue, improper communication, arrangements between pilot and bridge, and improper technical knowledge – especially in using new intentioned navigational equipment.

2.5.2 Organisational safety culture and safety management system

Darbra et al. (2007) carried out a study which aimed to assess the safety culture and hazard risk perception of Australian and New Zealand maritime pilots. They undertook this assessment as previous studies had not considered the operational culture and reliability of the controlled environment of ports and harbours. Furthermore, they defined safety culture as sets of beliefs and standards used to enhance the safety reliability by controlling operators working individually or as a team who are interacting together and with people outside the organisation. Accordingly, based on the pilots' shared values, the operational risks and economic and environmental issues could be mitigated, since human faults have been recognised as the main contributory factors involved in most accidents. Therefore, evaluations of the safety culture by identifying the weak links, which require further improvement, will enhance operational reliability by reducing incidents and their consequences. By contrast, the pilotage reliability analysis gives an indication to decision makers of any associated risks, which allows them to predict hazards in advance.

2.6 Pilotage hazard identification

Pilotage operations, as aforementioned, take place in a dynamic working environment. The associated hazards are varied and subject to certain circumstances. The main hazards within port pilotage operations can be identified through literature review and accident investigations.

According to Darbra et al. (2007), the term ‘hazards’ can be described as any event, activity, or phenomenon that can constitute harm to the operator, ship, port, the environment, or a combination of these. They defined ‘hazardousness’ in their study as ‘the potential to affect safety of ships' crew, cargo and environment’ (Darbra et al., 2007, p. 741). They identified the top 10 hazardous events (Table 2.1) and the top 10 likely events (Table 2.2).

Table 2.1. Top 10 hazardous events in pilotage (Darbra et al., 2007, p.742)

Rating	Top 10 hazardous events in pilotage
1	Starting/steering/anchoring equipment failures when manoeuvring or navigating
2	Poor boarding arrangements (e.g. incorrectly rigged pilot ladder, poor location, poor on-board access)
3	Failure of tug lines
4	Failure of ship’s master and/or personnel to correctly follow pilot’s directions (e.g. refusal, rejection, intervention by master)
5	Navigating and ship handling in marginal operating conditions when subject to commercial pressure
6	Readiness and efficiency of navigation/propulsion equipment misrepresented to pilot by master
7	Pilots navigate vessels outside published guidelines or limits (draft, higher swell, lower tide, etc.)
8	Incorrect operation of ship’s equipment (missed orders, incorrect interpretations, etc.)
9	Failure of regulator to enforce efficient regulations for safe navigation (e.g. for small craft, adequate UKC, passing rules)
10	Incorrect ship details provided to pilot/port (draft, efficiency of machinery, etc.) prior to pilotage

Table 2.2. Top 10 likely events in pilotage (Darbra et al., 2007, p.742)

Rating	Top 10 likely events in pilotage
1	Failure of ships to provide working environment conducive to pilotage (BRM, attentiveness, etc.).
2	Failure of ships to prepare and present informative mandatory passage plans.
3	Poor workplace design (e.g. wheelhouse instrumentation, location, accessibility, visibility, clarity, ergonomic layout, etc.).
4	Incorrect operation of ship's equipment (missed orders, incorrect interpretations, etc.).
5	Failure of regulator to enforce efficient regulations for safe navigation (e.g., for small craft, adequate UKC, passing rules).
6	Poor boarding arrangements (e.g. incorrectly rigged pilot ladder, poor location, poor on-board access).
7	Inadequate charts, navigation equipment and/or operating language in use on ships.
8	Engine starting/steering/anchoring equipment failures when manoeuvring or navigating.
9	Incorrect ship details provided to pilot/port (draft, efficiency of machinery, etc.) prior to pilotage.
10	Inadequate supervision and/or training of onshore service providers (VTS/Signal Station, lines, tugs)

2.7 Human Reliability Analysis (HRA)

The potential for major losses in terms of economics and even human life due to system complexity mark the need to improve human reliability analysis (HRA) (Swain, 1990). HRA is a systematic framework for assessing the contribution of humans to system risk, including the process of human performance evaluation and humans' associated impact on structures, systems, and complex systems (Su et al., 2015). In light of historic disasters such as Three Mile Island and Chernobyl, a realistic assessment of human error probabilities is a major goal of HRA. HRA could thus help to identify the weaknesses of a system at any operational stage, and those weaknesses could in turn be corrected before the occurrence of serious outcomes. The reliability of complex systems cannot be guaranteed. Complex systems could fail catastrophically at any operational stage, and failures due to operational complexity are inevitable (Perrow, 1994). Although noticeable improvement in operational technologies has been made, failures still exist due to human involvement (French et al., 2011). Accordingly, in complex systems, a deep operational understanding of human behaviour is essential. This understanding entails awareness of the operators' reliability in arranging and maintaining the safety barriers that influence the safety of the overall system.

Across HRA literature, many approaches have been proposed to analyse the human reliability and error quantification. According to Konstandinidou et al. (2006), HRA has always been a serious concern among safety and risk assessment analysts. The subjectivity and uncertainty of the methods traditionally used for evaluating the reliability of a human were the main reasons behind this concern. HRA development began in the nuclear industry in the 1960s (Bedford and Cooke, 2001; Kirwan, 1994). Since then, HRA has been applied across many well-known, high-risk industries, including the maritime (Yang et al., 2013; Martins and Maturana, 2013), healthcare (Lyons et al., 2004), aviation (Calhoun et al., 2014) and offshore and oil and gas (Akyuz and Celik, 2015) industries.

Different HRA techniques include hazards and operability analysis (HAZOP) (Chudleigh, 1994), a technique for human error analysis (ATHENA) (Dougherty, 1998), cognitive reliability and error analysis method (CREAM) (Hollnagel, 1998; Marseguerra et al., 2006), and human error assessment and reduction technique (HEART) (Williams, 2015). The different HRA techniques fall into three generations of HRA methods. The first generation used the probabilities of task failure, the adjustment factors based on performance conditions, and the error factors (French et al., 2011). The second generation of the HRA methods attempted to incorporate contextual effects such as tiredness, stress, and organisational culture (Barriere et al., 2000). The third generation has sought to allow for potential variation in response and recovery actions once an error chain has begun (Mosleh and Chang, 2004).

According to French et al. (2011), summative HRA and related approaches emphasise the use of quantitative and prediction approaches. The absence of well-developed and valid models of behaviour and organisations that can provide precision is noticeable. Successful development of an effective quantification model for a complex working environment is highly dependent on the availability of data, which are needed to validate the HRA model. In this research, different methodologies were proposed with the aim of developing an effective quantitative marine pilot reliability assessment framework that could handle high levels of uncertainty and lack of data. These steps and approaches are explained in detail in the upcoming consecutive chapters.

2.8 Highlighted factors on shaping human performance

Team reliability is vital in every dynamic working environment, and it requires operators to continually monitor situations and adjust their decisions accordingly (Rouse et al., 1992). Decision-making is a central process in all organisations, and a successful operation requires an exceptionally reliable team. Variation in the decision making process can be expected for a team conducting a pilotage operation, due to the dissimilarity of operators' responsibilities (Rouse et al., 1992). Therefore, developing a marine pilot reliability index will help decision makers to predict changes in a pilot's performance and maintain operational efficiency.

According to the guidance of the American Bureau of Shipping (ABS), the factors that are essential for overall organisational safety when selecting an operator for a task are as follows (ABS, 2003; Ramin et al., 2012):

1. Knowledge, skills and abilities shaped through an individual's basic knowledge, general training and experience.
2. Maritime-specific training and abilities such as certificates, licences, and other maritime-related skills, such as those relating to vessel or offshore installation.

3. Physical strength and personal capabilities and limitations (such as resistance to and freedom from fatigue), visual ability, physical fitness and strength, acute or chronic illness, and substance dependency.

4. Psychological and mental characteristics (such as individual risk perception), risk tolerance, and resistance to psychological stress.

5. Physical characteristics of an operator such as stature, shoulder breadth, height, functional reach, overhead reach and weight.

Based on a literature review of notable highly critical industries and the ABS Guidance stated above, this section discusses existing findings on human performance, which aids in forming an overview of what may be beneficial in developing proposed MPRIs for this study. Accordingly, the following sections are organised based on the ABS guidance, with the selection of factors for each sub-section based on related information contained in existing studies. Moreover, the factors included in each sub-section are widely used in various industries to assess operator performance. Accordingly, factors shaping human performance are presented as follows:

2.8.1 The contribution of knowledge on shaping performance

According to the IMO resolution A. 960 (2004), operators conducting a pilotage operation are required to have specialised work-related knowledge and experience in the pilotage operation area. The competent pilotage authority is obligated to encourage the establishment of a competent pilotage system within a port through assessing and maintaining the pilot’s qualifications with the support of additional maritime training. As a result his/her work-related experience is enhanced.

A qualified operator has a set of competencies, licences, and certifications that exhibit his/her achievement in complying with the minimum work-related knowledge required to carry out certain duties. These competencies cannot be achieved if they are not accompanied by training, enough knowledge about the nature of the operation, and a certain level of working experience.

In a port pilotage operation, a competent pilotage authority must ensure that the pilot holds an approved pilotage certificate, achieves a licence recognised by authority, and fulfils the minimum operational standard (IMO, 2004). The certificate must highlight any restrictions and limitations specified by the authority, such as maximum size, tonnage, and draft that the pilot is allowed to handle. Therefore, Section 7 of resolution A.960 (IMO, 2004) states that the pilot must have the necessary pilotage knowledge for certification purposes. This is outlined in 28 syllabi focusing on recommendations for training, certification, and operational procedures for maritime pilots other than deep-sea pilots. These syllabi are designed for a pilot who is designated to operate in a specific pilotage area. This is because knowledge of some of them (such as traffic separation scheme, bridges as an obstruction, and port channels) is not necessary in ports where they do not occur.

Training has been identified as one of the most dominant factors shaping organisational performance (Alvarenga et al., 2014). Lack of training within the maritime sector has been found to be a distinct cause of accidents (House, 2007), where specific training may include a set of compulsory or additional requirements (Riahi et al., 2013). As the human element accounts for 80 per cent of maritime accidents, the ISM code was implemented by the IMO in 2008 (Berg, 2013). This code addresses the issue of human element contribution by addressing the significant role that operator training and education can play towards safety performance. Therefore, the aim of the ISM code was to implement effective training and promote suitable qualifications and experience to reduce the probability of human error during maritime activities (Berg, 2013). As a result, tremendous efforts have been made aiming to trace the root cause of deficiencies in performance within maritime industries, particularly in relation to operators' non-technical skills (NTS) (Hetherington et al., 2006).

For instance, the crew resource management (CRM) training course was initiated based on the core NTS developed in many industries, such as aviation (Flin et al., 2003).

According to Rothblum (2000), the United States Coast Guard highlighted many critical areas affecting pilot performance. One of these factors was the particular training for a pilot, such as using radar, which was found to be crucial to a pilot's performance. It is the responsibility of the port authority, according to resolution A.960, to ensure that the assigned persons who are conducting pilotage operations are capable, technically qualified, and well experienced. This is generally confirmed by assuring they hold a certain required set of certificates and have taken special improvement courses based on what they need to use within the operations.

It is known that risk within the maritime industry is an inherent factor that can be reduced or acknowledged, but it cannot be totally removed (Berg, 2013). Marine operators experience risks on a daily basis, and this can be addressed if the operators have gained enough experience, training, and work-related qualifications to make proper decisions. Thus, decision making constitutes the central operational process in every critical industry, and it is manifested through a dynamic working environment which achieves operational goals and through employing knowledgeable, well-trained operators. Expert knowledge can be built most importantly through experience. Accordingly, the operator’s work-related experience has been identified as fundamental to every working environment in handling critical operational situations. It has been proven that a well-experienced operator has the capability to choose the most suitable option when undergoing high stress or time pressure (Yule and Brown, 2012). According to Klein’s investigation (1993), experts can often identify the most feasible operational option for a problem based on their experience rather following systematic options such as an operational checklist.

Experience is developed by the accumulation of knowledge or skills that are gained over time. In summary, work-related experience has been found to be fundamental in shaping an operator's capability to handle critical situations.

2.8.2 The contribution of fatigue on operator performance

Fatigue has been defined by Yule and Brown (2012, p. 47) as 'a state of sleepiness characterized by feeling drowsy or tired that results in a reduced ability to maintain concentration, make decisions, and carry out skilled tasks'. The word 'fatigue' describes the workers' feelings of mental or physical tiredness and depression in their daily working experience (Kim et al., 2009). A fatigued operator is usually unable to maintain work at the required level due to a lack of energy and motivation. As a result, forgetfulness, loss of memory, and diminished ability to think clearly will emerge in the subject (Kim et al., 2009). Thus, a review of the current status of safety within the maritime industry and the human element involved in operations indicated that fatigue was one of the most dominant factors which adversely influenced overall operational safety performance (Hetherington et al., 2006).

Studies have shown that there are potentially tragic outcomes from fatigue in terms of poor health and operators' diminished performance (Josten et al., 2003). The existence of fatigue can be expected at all operational stages and cannot be avoided due to working hours, sleep problems, shift length, work stresses, and working environment (Hetherington et al., 2006). Most of the factors that predict fatigue have been identified through different studies, such as working hours (Raby and McCallum, 1997), work stresses (Yule et al., 2012) and working environment (Undre et al., 2006).

Working hours can be defined by the number of working hours per day or the time of the day when the operator is carrying out his/her duty, as highlighted in healthcare (Yule et al., 2012), the maritime industry (Hsu, 2012), and aviation (Flin et al., 2003).

Seafarers have been identified as having the second-highest level of fatigue after rail operators, as they have the highest number of working hours over a 30-day period (Board, 1994). As Hetherington et al. (2006) reported the Cole-Davies study, which highlighted that the National Union of Marine Aviation and Shipping Transport (NUMAST) carried out a survey on 563 seafarers. Half of the surveyed seafarers were exceeding 85 working hours per week. Moreover, 66 per cent of these seafarers suggested that extra staffing was necessary to help reduce fatigue levels.

For instance, in the 24 hours preceding the Exxon Valdez grounding in 1989, the officer of the watch had had only 5-6 hours of sleep (National Transportation Safety Board, 1990), which highlights the contribution of fatigue to this catastrophe. Extended hours on duty and the accumulation of hours worked in the preceding three days lead to marine accidents associated with fatigue (Raby and McCallum, 1997). As a result, it has been proven that lack of sleep caused by extended working hours reduces an operator's clarity of thinking and causes him/her to become rigid in thinking (Yule and Brown, 2012).

The contribution of shift arrangements to fatigue has been pinpointed in different industries. Rigorous shift arrangements can lead to serious degradation in operational safety performance and poorer operator health (Embriaco et al., 2007; Iskera-Golec et al., 1996). Shift work interrupts the circadian rhythm of the body by disrupting sleep patterns, resulting in disrupted sleep cycles (Yule and Brown, 2012). Therefore, a quick recovery from fatigue can be expected when working just a single day or a few days' night shifts (Folkard et al., 2007; Spencer et al., 2006). This is preferable to having a continuous week of night shifts, which is considered the worst pattern of work, as it causes fatigue accumulation towards the end of the week with disrupted sleep (Yule and Brown, 2012). In addition, longer recovery from fatigue is associated with an increase in age, which explains why senior surgeons are taken off the on-call rota (Yule and Brown, 2012).

Thus, it could be inferred that this would also be found within the maritime domain with additional issues such as rolling, pitching, vibration, and noise, which could magnify any present effects of shift work-based fatigue (Harrison and Horne, 2000; McNamara et al., 2000).

Work stresses have a direct influence on an operator's technical and non-technical performance within the maritime industry. Typical conditions for seafarers feature high operational demands (Hetherington et al., 2006) due to factors such as shorter sea passages, higher levels of traffic, reduced staffing, and rapid turnarounds. As reported by Cole-Davies (2001), the NUMAST carried out a survey on 1,000 officers and found that 84 per cent felt that stresses have become a dominant fatigue factor. Therefore, working stresses have been identified as an influential factor on operational productivity and operator health (McLeod, 2011; Cooper et al., 2001). Experiencing a high level of working stresses for an extended period of time will lead to the degradation of an operator's mental capacity and physical health outcomes (Quick et al., 1997).

The influence of stress has been proved to be the main cause of diminished working memory during a stressful time (Yule and Brown, 2012). Change in an operator's cognitive function in association with acute working stresses has been linked to a significant reduction in memory. This has a serious impact on overall safety perceptions, decision making, and task management (Yule and Brown, 2012). Therefore, an operator who is inexperienced in handling critical situations and managing tasks may be unable to make the proper decision in an acutely stressful situation.

Working environment has been found to significantly influence operator fatigue, which as a result affect operator performance in most critical industries. Aviation (Flin et al., 2003), health (Undre et al., 2006), and maritime (Riahi et al., 2012) have all suffered losses due to improper enhancement of the working environment.

Different studies have highlighted factors that affect operators' surroundings, which help to either maintain or degrade their operational standards (Chauvin et al., 2013; Berg, 2013; Celik and Cebi, 2009; Darbra et al., 2007). These factors include, but are not limited to, physical working environment (Celik and Cebi, 2009), ergonomic design (Riahi et al., 2013), and the status of the operative environment (Vincent et al., 2004).

In a safe working environment, safety and professional practices are expected to be strengthened through maintaining an operator's behaviour and providing management support (Saeed et al., 2016). In this working environment, accidents tend to decline as a result of safe operational practices. Therefore, the operators' relations with managers and participation in workplace health and safety management have been proven to be significant in overall workplace safety (James and Walters, 2002; Bhattacharya and Tang, 2013).

The nature of pilotage operations requires the pilot to work in shift patterns based on the number of ships calling at that particular port and the time of calling. Prolonged working hours are expected, which vary from one port to another and are subject to different factors (channel distance, tide variation, number of tugs available, etc.). The operational demands require pilots to transfer between ships through a pilot boat. When travelling, the boat will be exposed to waves, vibration, humidity, and noises, which may make the pilot become drowsy or even worse. The pilot is required to climb a pilot ladder and, in some cases, this pilot ladder lies along the ship's freeboard, which may reach a height of more than 10 metres. Sometimes, the ladder is not properly maintained and, in addition to the high level of waves due to weather turbulence, this may result in the pilot falling from height into the pilot boat or into the sea. This could cause serious injury or even death. Therefore, the way in which the pilot is transferred to and gets on-board the ship increases pilot stress. In addition, climbing this ladder and the pilot's ability to transfer quickly both require a high level of physical strength. A pilot's working environment tends to lead to a high level of stress, and this by its nature leads to a high level of fatigue. The high level of fatigue will lead to health problems and degrade an operator's cognitive capacity.

Darbra et al. (2007) investigated the link between working environment and safety culture, which causes fatigue within an organisation. Commercial pressure and the depression of wages resulting from bad safety culture management leads the pilot service provider to not maintain effective fatigue management, carry out proper pilot launch checks, or provide pilots with training (Darbra et al., 2007).

2.8.3 The contribution of operator mental and personal characteristics

The knowledge base and technical proficiency of employees within most well-recognised high-risk industries are essential, and a vast amount of a company's resources are spent on enhancing their technical proficiency. Around the mid-1980s, the aviation industry's focus was on aircraft technological and technical aspects and pilot training (Moorthy et al., 2005). This followed research carried out by the National Aeronautics and Space Administration, which revealed that human errors constituted around 70 per cent of reported accidents due to failures in interpersonal communication, decision making, and leadership (Helmreich et al., 1999). Moreover, operators' NTS and their component failures (situational awareness, decision making, etc.) which were revealed in most accident analysis lead to adverse events in increasingly complex organisations, even if the operator had a high level of technical competencies (Sharma et al., 2011). Since the 1980s, researchers have tried to tackle the problem caused by the deficiency of NTS through developing a behavioural marker tool (Sevdalis et al., 2009; Flin et al., 2003; Yule et al., 2006; Yule et al., 2008; Sevdalis et al., 2008; Healey et al., 2004; Salas and Prince, 1997). This tool is widely used in different high-critical industries which aim to structure the required training needs and evaluate these skills. It surfaces in aviation (Flin et al., 2003), marine (Saeed et al., 2016), and health (Fletcher et al., 2004; Yule et al., 2012).

For this reason, an intensive literature review has been carried out to discover the main components of the operator's NTS from different disciplines. The review displays that operators' NTS are composed from a set of social and cognitive competencies that exhibit the operator's ability to perform his/her work. Variability was observed in researchers' points of view on the factors that adversely influence NTS due to the nature of the industry. In summary, proper enhancement of operators' NTS in high-risk industries is highly crucial in order to eliminate the consequences of human error (Helmreich et al., 1999).

One of the identified factors constituting operator NTS is personal skill for making proper decisions. The decision-making (DM) process has been defined by Flin et al. (2008:41) as 'a process of reaching a judgement or choosing an option, sometimes called a course of action, to meet the needs of a given situation'. DM is an essential skill for reliable operations in any high-risk industry, and it is identified widely in all investigations concerning the operator's NTS (Ramin et al., 2013; Yule et al., 2012, Moortyh et al., 2005; Flin et al., 2003).

Intensive efforts have been made by researchers to develop decision-making techniques that can be used by key decision makers (Flin et al., 2008). These techniques are subject to situations and circumstances that are sensitive to safety-critical decisions (Saeed et al., 2016). This leads to variability in identifying the main components of NTS. A psychologist researcher at NASA studied different styles of DM made by a pilot in different situations. The final statement of this research was: 'Crews make different kinds of decisions, but all involve situation assessment, choice among alternatives and assessment of risk' (Orasanu and Connolly, 1993, p. 138). Thus, it is apparent that the degree of DM process varies and is subject to multiple cognitive processes depending on task conditions and decision requirements (Flin et al., 2003).

It is worth mentioning that the process of DM encompasses a set of structural sequences as per Flin et al. (2003).

Table 2.3. Structural sequences of the decision-making process (Flin et al., 2003, p. 109)

Element	Definition
Problem definition and diagnosis	Gathering information and determining the nature of the situation. Considering alternative explanations for observed conditions.
Option generation	Formulating alternative approaches for dealing with the situation. The opportunity for this will depend on available time and information.
Risk assessment and option selection	Making a judgement or evaluation of the level of risk/hazard in alternative approaches and choosing a preferred approach.
Outcome review	Considering the effectiveness/suitability of the selected option against the current plan once the course of action has been implemented.

DM, as a cognitive process, is a hidden process that cannot simply be predicted and evaluated. However, it can be inferred by an operator’s behaviour. When a decision maker communicates a decision to other team members, it is essential for a decision maker to bear various factors in mind that may influence member duties in order to comply with that decision, such as available options and support, crew qualifications and demands, company standard procedures and policies, etc. (Saeed et al., 2016). Therefore, when making a decision, operation-related information must be collected that helps to determine and evaluate the current situation at that particular time.

During a pilotage operation, the pilot may face an engine failure problem while transiting through the port channel that endangers the port by blocking the channel for other users. The pilot is first required to identify the problem and generate different options to preserve the port channel. According to Adelman et al. (1995), generating options is a critical process when making decisions. Therefore, in this critical situation, the pilot will formulate different approaches to deal with the failure. This approach is highly dependent on time constraints and information availability (Flin et al., 2003). In a situation where a ship’s engines fail while manoeuvring the ship inside the port, the pilot can decide either to drop the anchor using the bow thruster or obtain external support from the tugs.

After the decision makers have generated options, risk assessment must be carried out in order to select from these generated options. The word ‘risk’ means a small hazard that may turn into a critical situation (Saeed et al., 2016). Accordingly, the decision maker is required to evaluate the risks associated with the generated options to weigh the risks’ probability. In the above-mentioned example of engine failure while manoeuvring the ship inside the port, dropping anchor may not be the best option at that time, as failure to choose the proper anchor will increase the risk of collision or even grounding.

Accordingly, when the pilot chooses an option, its consequences must be reviewed in order to implement a course of action. This requires the decision maker, when choosing an option, to consider the effectiveness of the selected option according to the current operational demand.

The DM process is categorised as one of the most important NTS required by an operator in enhancing operational reliability in most high-risk industries. In the maritime context, for instance, a poor decision by the master of a ship may lead to the loss of lives, loss of the ship, or pollution of water (Riahi et al., 2012). In 1967, the grounding of the tanker Torrey Canyon resulted from a poor decision made by the captain. This captain decided to save six hours in reaching Milford Haven by taking a direct route to arrive at high tide. In this case, commercial pressure had an influence. Although the short course he chose was deep enough to cross safely, the ship went aground crossing the area around the Scilly Isles while trying to avoid collision with a fishing boat (Hetherington et al., 2006).

Consequently, there is a distinct link between commercial pressures, situation awareness (SA), DM, making decisions under stress, and these factors' have an effect on operator reliability and operational safety.

To make proper decisions, the operator is required to comprehend operational processes by collecting the required data and enhancing operator awareness. SA skill has been identified as a major key factor in accident causation which impacts the safety of most critical industries (Salmon et al., 2009; Flin et al., 2008). Poor performance may occur as the result of scarcity of operational information, improper planning, heavy workload, poor DM, improper team building, and fatigue. SA skills mean developing and maintaining awareness of surrounding changes during an operation (Johnston et al., 2011). This type of skill is the personal ability to model mental processes in accordance with what is going on at the time to make adequate decisions that satisfy the demands of the current situation (Salmon et al., 2009).

Researchers have made significant efforts in tracing the way that SA develops over time during an operation. The significance of developing a behavioural marker assessment tool to assess the performance of operators in different disciplines was due to the fact that SA, as one factor that constitutes operators' NTS, has a distinct importance in shaping human performance (Flin et al., 2003; Livingstone, 1994; Healey et al., 2004). In addition, the crew resource management (CRM) course has been developed to give operators proficiency in NTSs, and it is widely applied in different safety-critical industries.

Endsley (1995, p. 36) defined SA as 'the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future'. Endsley (1988) categorised SA into the following three levels:

1- Correct perception of main elements must be shaped by the operator in order to project an accurate operational picture;

2- Combining, interpreting and storing all collected information that helps to form a situational image which helps to understand the significance of particular objects and events; and

3- For projection purposes, acquired information from steps one and two must be combined.

Endsley (1995) introduced a generic model that constituted the above three levels. The model mainly focused on the influence of SA on an operator's DM process in crisis conditions. The model shows the factors that critically influence an operator's SA. As per Salmon et al. (2009) and Flin et al. (2008), a chain of information can be obtained from Endsley's three-level model. The perception of the elements in the environment is in the first level. The second level involves comprehending the information gained in the first level, and future status projection forms the third level.

The operator can predict what is going to happen in the future as the SA is defined through a set of operational processes. He/she is required to gather important information which will help him/her to be aware of the next step at that stage of the process. In fact, the 'perception of elements in the current situation' was predicted and information was gathered through the first level of Endsley's SA model (Ensley, 1995). For instance, the ship's course and speed, traffic density, and weather conditions are examples of the main elements required for the bridge team to develop the current situation at this stage (Saeed et al., 2016).

The operator is required to process and assess the significance of the information gathered from different resources throughout the operation. This level is the second level of Endsley's model and means that decision makers are able to form a clear picture of the current situation through highlighting the significant factors in implementing procedures according to the current event. For instance, a ship's officer must evaluate the situation when two methods for position fixing result in different outcomes, showing that the ship is not in the same place (Saeed et al., 2016). As the expected result has changed, an investigation must be carried out to control the situation and implement orders in the right way. This process can only be tackled by an experienced operator. Thus, a novice operator may not be able to go beyond level one of Endsley's model, 'perception of elements in the current situation', and interpret the information gathered. Therefore, experienced decision makers will be capable of assessing the situation in achieving the desired operational goals (Endsley, 1995; Flin et al., 2008).

Based on the information gathered and its interpretation, the third level allows the decision makers to predict and project future events (Mishra et al., 2008). An experienced decision maker's future prediction allows him/her to take the necessary action to avoid unfavourable events that may occur.

Therefore, the three levels of SA can be summarised as follows:

> SA is based on far more than simply perceiving information about the environment. It includes comprehending the meaning of that information in an integrated form, comparing it with operator goals, and providing projected future states of the environment that are valuable for DM. In this respect SA is a broad construct that is applicable across a wide variety of application areas, with many underlying cognitive processes in common (Endsley, 1995; p. 37).

In summary, evaluating a situation properly requires the careful identification of key factors that influence SA. It is apparent from different models (i.e. Endsley's model) that the correlation between factors (e.g. experience, training, state of the environment) was found to be inherent, meaning that the factors influenced each other. The objective of this research is to identify the degree of influence of other identifiable factors on performance. For instance, a pilot who is suffering from fatigue tends to be sensitive and irritable towards other team members. This means that other team members will not communicate what is going on during their duty. As a result, the information flow will substantially decrease. This information may be important for projection purposes and, as a result, decisions made will not satisfy operational standards.

Communication skills (CS) are another key factor in effective and safe task achievement in any safety-critical industry (Flin et al., 2003). These skills are categorised as central within other NTS in that its effectiveness will contribute to overall production safety and performance (Lamb et al., 2011). The criticality of inadequate CS reflects lack of SA, poor teamwork, and poor operational decisions. As per Yule et al. (2006), the role of CS is to regulate, control, motivate, express feelings, and convey information to other team members involved in an operation. Lack of transparency in communication between members is the root of most conflicts that occur during an operation (Blundel and Ippolito, 2008), as evidenced by Gawande et al. (2003) that 43 per cent of errors made by surgeons were due to communication failure. Thus, the way in which the information will be expressed or transmitted must be decided in advance between team members.

Flin et al. (2008) defined communication based on the way the information has been transmitted. CS is an important skill to all parties engaged in the pilotage operation, such as the shipmaster, pilot, tug master, VTS operator, and harbour master. Different researchers have identified the significance of communication and its influence on teamwork effectiveness as a key skill to ensure an acceptable level of understanding of a shared operational situation and to complete tasks efficiently (Yule and Brown, 2012). Accordingly, enhancing an operator’s CS will improve the mental model shared between team members (Flin et al., 2008).

Eliminating doubt and confliction can be achieved through clear and concise communication in regards to identifiable issues that influence the safety of the operation (Kleij, 2009). Operator language capability is one of the main identifiable problems found in every domain that needs CS, such as health (Yule and Brown, 2012), nuclear (Saeed et al, 2016), and shipping industries (Ramin et al., 2012). With regards to shipping, Hethrington et al. (2006) observed that the level of language fluency required to operate ships safely has not yet been achieved, and this is still the case today.

Different studies have categorised communication as an independent operator's NTS (Ramin et al., 2012; Moorthy et al., 2005), while others have included it within teamwork building skills (Yule et al., 2008; Undre et al., 2006; Fletcher et al., 2004). This variability in category is due to different views on structuring the particular study's model. However, in both ways, communication is inherently an important medium for information flow that significantly affects the level of SA and DM process between team members. The differences in perspective can be said to be due to validation purposes, assessment techniques, or the researcher's point-of-view. In this study, CS has been categorised independently because of the nature of the pilotage operation and the independent characteristics of the main operational players involved where that skill can be diminished if the method of communication fails.

There is widespread acknowledgement in high-risk industries that leadership (Yule and Brown 2012; Riahi et al., 2013) and teamwork (Sasou and Reason, 1999) are crucial for efficient and safe team performance. Higher operational performance can be achieved with committed, highly qualified leadership (Little, 2004), and teamwork (Sasou and Reason, 1999). One of the most significant positive moments can be seen when an effective collaboration between members takes place after a co-worker has mishandled an operation. However, whilst teamwork can be significant in helping to overcome errors during operational stages, it can also be a main motivation for error development. This is the case when someone in a leader role fails to regulate operational standards and policy towards a corrected procedure.

As per Berg (2013), desirable leadership qualities, which can improve teamwork effectiveness, can be shaped through the following criteria:

- Establishing clear two-way communication,
- ‘tough empathy’
- Openness to criticism,
- Empathy towards cultural diversity,
- Capable of motivating people and developing a community atmosphere,
- Coping with an operator’s limitations, and
- Being a key team player.

Therefore, the distinction between being a leader and being a manager is that a leader has the capability to inspire and motivate other team members, whereas the manager works to organise the existing operation and proposes the next operational process (Lau et al., 2014). Teamwork and Leadership skills (T&L) support each other in every organisation driven by a human element. The definition of leadership is the process of a social influence that encourages workers to pursue a set of goals (Quinn and Spreitzer, 2006). The importance of a leader appears during organisational crises as he/she tries to make sense of the situation (Combe and Carrington, 2015).

However, an exceptional solution is required when new operational technical and routine issues exist on a daily basis, which requires adaptive, experienced, and knowledgeable leadership. Therefore, five features of leadership adaptability were also identified by Eubank et al. (2012) as follows:

1- Identify the adaptive challenge and frame key questions and issues,

2- Let the organisation feel external pressures within a range it can stand,

3- Challenge current roles and resist pressure to define new roles too quickly,

4- Expose conflict or let it emerge, and

5- Challenge unproductive norms.

These features of leadership necessitate the leader being present when a problem occurs in order to handle the new challenges. Effective leadership also requires proactive operational thinking and assigning new members' roles as required towards solving the problem (Aronson et al., 2006). In such an operational situation, the leader is always subject to operational stresses that need him/her to achieve the goal with an optimum level of productivity and efficiency. Accordingly, operational stresses are a common feature at every operational stage that have a vital influence on operational outcomes through shaping worker productivity. Stresses are an external factor that affect an operator's mental condition and limit his/her ability to lead and perform assigned duties (Healey et al., 2004). According to Gill et al. (2006), there is a need to overcome the effect of stress by developing a strategic process that helps to reduce its occurrence. The responsibility of a leader in any industry is to satisfy the operational requirements to achieve the highest goal. This works by monitoring the process throughout the organisation (Aronson et al., 2006).

In the pilotage operation, most of the reported accidents within ports have been caused by bridge team members' failure to develop a positive teamwork atmosphere. Although the pilot, when he/she comes on board to handle the ship, has a responsibility to share similarly to the ship's team members, the master's role is to ensure a positive working atmosphere by encouraging team members to work and share their responsibilities towards achieving the overall operational goals. Thus, professional leaders tend to develop more realistic goals by conducting a risk assessment at each operational stage. This will reflect the ability and quality of that leader in handling the operation effectively.

As the pilotage operation is based on teamwork and requires the sharing of information and cooperation, effective teamwork development is recognised as an important factor in achieving a reliable operation in this (and any) safety-critical industry (Riahi et al., 2012). Teamwork must function effectively at the early operational stage to work towards a common operational goal (Hetherington et al., 2006). This requires coordination, cooperation, and CS to share information with other team members at every operational stage. Well-known safety-critical industries such as maritime, nuclear, health, and aviation are heavily reliant on T&L effectiveness (Berg, 2013; Flin et al., 2008). This dependence on teams has a significant impact on overall operational objectives and must be considered in every organisation.

2.8.4 The impact of operator physical ability on operational performance

The fitness and strength of the operator are crucial in many high-risk industries, and physical ability plays a significant role in successful operations. However, fatigue caused by a variety of factors (see Section 2.8.2) was found to have significantly impacted operator performance (Kim et al., 2009). This relationship occurs naturally in every field that requires a high level of physical and mental activity, which is the case in pilotage operations. The demanding nature of this job requires the pilot and other operators to maintain a high level of physical and mental strength throughout all operational stages. Therefore, a link between human fatigue and operator fitness and strength has been identified. Moreover, fatigue has an influence on operator NTS, which means that fitness and strength have been associated with operator NTS and TP. Consequently, it is important that the port authority, when assigning a pilot to handle a ship, ensures that the pilot's physical and mental strength have been properly maintained, as per the IMO resolution A.960 (2004) and the ABS guidance (2003). The fundamental purpose of the pilot fitness assessment is to ensure that the individual pilot is fit to handle ships calling at the port.

According to IMO resolution A.960, the port authority must ensure that a pilot complies with minimum requirements of medical fitness and strength (IMO, 2004). It is known and recognised within the industry that when an operator becomes older, they may suffer from illnesses due to the nature of the operation and fatigue associated with the required duties (Hetherington et al., 2006). A reduction in mental capacity has also been observed as people age (Sturman, 2003), and muscle strength has also been identified as reducing after the age of 50 (Riahi, 2010).

The performance of operators in different professions has been confirmed as changing over time (Sturman, 2003). Despite the huge effort made to enhance operator performance (Flin et al., 2003; Aronson et al., 2006; Yule et al., 2012), different organisations know relatively little about the influence of natural causes that provoke fluctuations in operator performance (Sturman, 2003).

The operator age (OA) was found to play a significant role on performance level, along with other temporal variables (i.e. experience, organisational tenure) considered in Sturman’s (2003) investigation. Job experience, as explained in section 2.8.1 above, requires the accumulation of work-related knowledge from actions, practices, and perceptions related to the assigned duty, which is inherently tied to time scale (Sturman, 2003). However, as an operator gains work-related experience, he/she is getting older. OA can indicate how the performance of an experienced operator changes over time (Waldman and Avolio, 1993). Riahi et al. (2012) investigated the influence of age on performance and found that operator’s strength after age 25 generally decreases at a rate of about 1 per cent per year, remaining relatively high until the age of 50 before starting to decline by 10 per cent per year.

The negative relationship between age and performance has been confirmed, as age increase causes a deterioration in physical and mental strength (i.e. speed thinking, agility and coordination) (Mendes, 2013). As a result, a reduction in physical capacities and coordination, flexibility, strength, and power can be expected as an operator ages.

It is worth mentioning that it is not necessarily always the case that performance degrades with age. Therefore, the effect of each highlighted criterion in this section does not necessarily have a direct influence on performance. However, an accumulation of these effects may significantly influence performance over time. Furthermore, these characteristics tend to differ across pilots.

Another significant concern in maintaining higher performance is subject to operator health. Health issues (HI) are a major concern for both operators themselves and entire organisations. Approximately 80 per cent of organisational accidents in many high-risk industries are caused by human error. In maritime sectors, Hetherington et al. (2006) and Flin and Mearns (2006) have identified factors strongly associated with accidents at sea, and they found that operator health was one of these factors. HI can be a result of human fatigue accumulation (Bloor et al., 2010). Moreover, HI were found to be associated with the nature of work, geographical location, stress at work, prolonged working hours, commercial pressure, and organisational culture.

In different studies, factors found to be correlated with HI were fatigue, stresses, and health problems (Berg, 2013, Riahi et al., 2013; Smith et al., 2008). Fatigue has a direct influence and is considered a major risk factor in operators’ mental health (Smith, 2007). Conversely, impaired operator health is a key risk factor in operator fatigue (Smith et al., 2006). The link between fatigue and health problems has been identified as key in ensuring safe operations (Wadsworth et al., 2008, Mohren et al., 2001).

The nature of the pilotage operation requires the pilot to be physically and mentally fit at all times during service as a pilot. The pilot must be able to climb up a ship, where in some cases the freeboard is more than 10 metres high, which is followed by a high cognitive demand to guide the ship safely owing to, but not limited to, surrounding traffic density and weather conditions. Therefore, it is important for the port authority under the requirements of resolution A.960 to maintain the pilot's proper health and physical condition at all times.

Performance changes over time (Sturman, 2003), which means that an operator is developing his/her experience after a period of time, and meanwhile, getting older. As per Riahi (2010), body strength reaches a peak at 50, followed by a decline of about 10 per cent per year. However, this does not necessarily always occur at this age. The process of higher degradation may begin before this age, for example, depending on the operator's lifestyle and condition. Thus, as OA, degradation of physical and mental strength (i.e. thinking speed, agility, and coordination) can be expected (Mendes, 2013).

2.9 Research gap

The following research gaps were identified by conducting a literature review highlighting previous efforts in assessing human reliability in different industries:

1- Previous efforts to assess the reliability of an operator focusing on specific factors independently, rather than considering other factors more holistically;
2- Comprehensive guidelines that would show how an operator in a complex socio-technical working environment can be effectively assessed are unavailable;
3- A lack of studies on factors believed to be essential in assessing the reliability of an operator and how they can be assessed;

4- A need to highlight the degree of interdependence between identified factors and how they influence each other;

5- A lack of information on the pilotage operation, including how it is conducted and regulated, as well as information on participants involved in the operation;

6- Within marine port operations, an urgent need to develop an effective and rational quantitative reliability assessment tool (Board, 1994) capable of assessing the reliability of humans involved in a highly uncertain working environment.

Accordingly, this study aims to fill the gaps identified in the literature through systematic methodologies that support realisation of the study objectives.

2.10 Conclusion

Within this chapter, an overview of pilotage operations has been conducted showing the significance of the operations in global logistics. Marine accidents remain a major concern for port management, port stakeholders, and the public. A number of reported marine accidents indicate that human error is the most dominant contributing factor across the analysed data. The lack of an assessment model to assess the reliability of a human element within the maritime industry was mentioned by researchers, and the need to develop an effective tool is urgent. The lack of understanding on how the human element contributes to port safety has been highlighted. Different organisations take some steps to analyse and develop their tools to evaluate human performance. These efforts were also highlighted in order to examine the feasibility of the application of such identified models in maritime operations. Moreover, most of these models have been presented in an independent form, which is believed, to some extent, to not be feasible. The American Bureau of Shipping has highlighted different sets of essential factors when selecting operators to maintain overall organisational safety. In light with these factors, this chapter has comprehensively detailed other industries' efforts to identify the most dominant performance shaping factors. Previous studies have focused on factors influencing the operator's reliability independently. This approach does not effectively mitigate human error, as evidenced by the continuous existence of error. Moreover, these studies have not identified the degree of correlation between factors as one set. Therefore, this investigation integrates the aforementioned factors that challenge operators' reliability during pilotage operation as one set. Moreover, these factors require further examination for applicability to incorporate them into the proposed model in a holistic form. The next chapter aims to highlight the current organisational practices, as it found an absence of this information within the literature. The aim of this step is discussed in detail within the next chapter.

Chapter Three: Current pilotage operation theory and practices

3.1 Chapter Summary

This chapter highlights the current organisational working practices in the maritime industry, particularly those working practices during marine port pilotage operation and it is aimed at developing an effective model to be used in solving pilotage operational issues. This investigation has been conducted sequentially over three phases. Firstly, in terms of research design, the researcher has chosen to conduct a qualitative investigation, whose usage is justified in this chapter. Secondly, in terms of research tools and data collection, the researcher has collected data from a major marine port using three different data sets obtained by conducting field observation, focus-group interview and analysing four incidents, which occurred during marine pilotage services at this port. Thirdly, in terms of data analysis, the researcher identifies the main pilotage operators involved in pilotage service and their roles. Moreover, it highlights the main criteria constituting the reliability of a marine pilot. Lastly, it analyses four marine port pilotage incidents to partly validate the findings obtained from the interviews. The result obtained from this chapter will be used for the quantitative research analysis that would be presented in chapter four. This chapter's investigation processes are presented in Figure 3.1.

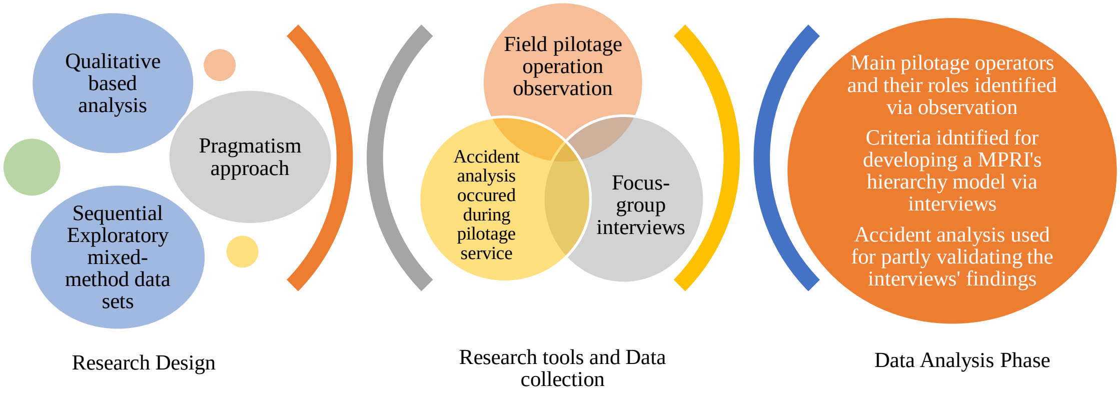

Figure 3.1. Chapter investigation process

3.2 Introduction

Accidents in the maritime industry have serious consequences, and a major contributory factor is identified as human error (Ramin et al., 2012; Hethrington et al., 2006; Safahani, 2015). According to P&I Club and the UK MAIB, human error was a root of 75-96 per cent of reported accidents (Rothblum, 2000; Ung and Shen, 2011; Ramin et al., 2012). Based on Hsu’s (2012) investigation, there was a significant increase in marine accidents within the last century, and the accidents have mostly occurred during ship/port interface. Therefore, to handle different types and sizes of ships, a high level of safety is required during a pilotage operation. The aim of this study is to contribute to developing and assessing the reliability of marine pilots during pilotage operations by investigating the current pilotage practices after analysing empirical data from this study. Subject to the lack of information on factors shaping marine pilot reliability, the literature has highlighted efforts made to identify human performance shaping factors. The applicability of these factors varies depending on many elements. These elements must be carefully examined by employing effective research methods capable of elucidating beliefs around the topic. For this reason, this chapter analyses data collected during real pilotage operations within a seaport. The data was gathered by observing pilot’s actions and procedures conducted within marine pilotage operations. The employed research methods are described in more detail in the following section.

3.3 Research background

3.3.1 A brief review of qualitative methods

Qualitative research methods are widely used across different disciplines in studies that seek to understand phenomena in specific settings (Golafshani, 2003). Unlike quantitative research, qualitative research produces findings that cannot be identified when using statistical or quantification research methods (Strauss and Corbin, 1990). The qualitative approach's philosophy describes developing knowledge in a particular field by determining the nature of that knowledge. This procedure is essential for identifying knowledge that cannot be described quantitatively. Accordingly, an analysis of several philosophical approaches is essential to scholars in order to select the most appropriate approach for the selected study.

According to Easterby-Smith et al. (2015), the researcher is required to clarify the philosophical assumption underlying the research methodology. Therefore, the researcher is required to specify under which paradigm the research is positioned. The research is significantly influenced by the paradigm selection, as it includes the framing and comprehension of the highlighted phenomena (Wahyuni, 2012).

3.3.2 Research paradigms

Research paradigms have been defined as "a set of fundamental assumptions and beliefs as to how the world is perceived, which then serves as a thinking framework that guides the behaviour of the research" (Wahyuni, 2012; p. 69). In conducting research, the researcher must ascertain the most appropriate philosophical paradigm at the beginning of the study in order to propose a viewpoint onto the nature of knowledge (ontology) in addition to the method used to know it (epistemology) (Creswell, 2009). The concept of 'ontology' refers to the researcher's perspective and understanding of the nature of social reality, whereas 'epistemology' encompasses the nature of knowledge and how it can be attained, with the behaviour of subjects not being influenced in any way (Ary et al., 2018; Creswell, 2009).

The fundamental philosophical research paradigms are positivism, realism, interpretivisim, and pragmatism (Table 3.1) (Saunders et al., 2012; p.119). These paradigms consist of three dimensions, namely ontology, epistemology, and axiology.

Ontology focuses on the nature of reality and existence, whereas epistemology emphasises the theory of knowledge, and axiology focuses on the research values (Easterby-Smith et al., 2015; Saunders et al., 2012). These paradigms have a significant impact on research and aid the researcher in understanding appropriate exploratory processes. Table 3.1 provides an insight into how to employ these paradigms and prompts the proper selection, which is dependent on the nature of the research and data analysis methods employed.

In this chapter, the researcher obtains data via operational observations, interviews, and operational accident data analysis, which require the researcher to adopt a paradigm that can handle the processed data. Moreover, the nature of the collected data is partly analysed quantitatively (see Chapter 4) and partly qualitatively. Therefore, the most appropriate approach for this research is ontological pragmatism.

3.3.3 Pragmatism approach

Pragmatism encompasses a mixed-methods approach, which is known as the third research method (Tashakkori and Teddlie, 2010; Johnson and Onwuegbuzie, 2004; Mayring, 2007). Methodological considerations arise in relation to ‘instrumentation and data collection’ (Cohen et al., 2013:5). The mixed-method approach uses both quantitative and qualitative research methods either independently to one another concurrently or sequentially, where the results obtained from one paradigm can be used to inform the other paradigm and address the research questions (Creswell, 2009). Venkatesh et al. (2013) noted that, “regardless of the type of research design used, the key characteristic of mixed-methods research is the concurrent or sequential combination of qualitative and quantitative methods within a single research inquiry”. In addition, Guba and Lincoln (1994) suggested that, both qualitative and quantitative methods may be used appropriately with any research paradigm. Questions of method are secondary to questions of paradigm, which was defined as the basic belief system or world view that guides the investigation, not only in choices of method but in ontologically and epistemologically fundamental ways.

According to Saunders et al. (2012), the usefulness of pragmatism is that it allows the researcher to concurrently position him or herself in positivist and interpretivist investigations. In addition, this approach applies a practical integration of different perspectives to support collect and interpret data. Accordingly, the researcher can achieve valuable insights into a phenomenon that may not be comprehended using only one paradigm. Therefore, pragmatism contemplates both real effect and practical consequences as essential mechanisms of meaning and truth (Venkatesh et al., 2013).

3.4 Selecting a research method

A key component of any research is choosing a research method. Choosing an adequate research method allows the researcher to achieve research objectives. Researchers must first state the research design and the data collection process, along with the tools necessary to analyse data. Clarifying this information provides the researcher with a systematic approach that can organise the researcher’s work and help achieve research goals. Research design has been defined as “a plan of the research project to investigate and obtain answers to research questions” (Blumberg et al., 2014). The advantage of designing a research project is to elucidate the research limitations by highlighting the setting of the study, the investigation type, the unit of analysis, and the issues established for further research. The diversity of research methods employed to investigate problems in a work place characterised as highly dynamic can be considered a major strength; they can be broadly categorised into two methods: quantitative and qualitative (Lee and Hubona, 2009; Myers and Avison, 2002; Sidorova et al., 2008). However, many scholars have combined the qualitative and quantitative methods in the same research, which is referred to as the mixed-methods approach.

The mixed-methods approach was defined by Johnson and Onwuegbuzie (2004, p.17) as “the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study”. Similarly, Creswell (2009) defines the mixed-methods approach as “an approach to inquiry that combines or associates both qualitative and quantitative forms. It involves philosophical assumptions, the use of qualitative and quantitative approaches, and the mixing of both approaches in a study”.

The advantage of using the mixed-methods approach is that it could help in highlighting theoretical credible answers to the topic in question by providing assistance that helps overwhelm practical or cognitive barriers associated with carrying out this particular type of research (Tashakkori and Creswell, 2008). It is worth mentioning that the researcher must have the ability to handle considerable paradigmatic, cultural, cognitive, and physical challenges to employ the mixed-method in a research study (Mingers, 2001). Moreover, using the mixed-method approach, especially if it is built on a common scientific basis, is vital to advancing and sustaining the traditions of methodological diversity in a research and creating a cumulative body of knowledge in a topic of investigation (Venkatesh et al., 2013).

Table 3.1. Comparison between the four research philosophies (Adapted from Saunders et al., 2012; p.119)

Research Philosophy	**Ontology:** the researcher's view of the nature of reality or being	**Epistemology:** the researcher's view regarding what constitutes acceptable knowledge	**Axiology:** the researcher's view of the role of values in research	**Data collection techniques most often used**
Positivism	External, objective and independent of social actors	Only observable phenomena can provide credible data, facts. Focus on causality and law like generalisations, reducing phenomena to simplest elements	Research is undertaken in a value-free way, the researcher is independent of the data and maintains an objective stance	Highly structured, large samples, measurement, quantitative, but can use qualitative
Realism	Is objective. Exists independently of human thoughts and beliefs or knowledge of their existence (realist), but is interpreted through social conditioning (critical realist)	Observable phenomena provide credible data, facts. Insufficient data means inaccuracies in sensations (direct realism). Alternatively, phenomena create sensations which are open to misinterpretation (critical realism). Focus on explaining within a context or contexts	Research is value laden; the researcher is biased by world views, cultural experiences and upbringing. These will impact on the research	Methods chosen must fit the subject matter, quantitative or qualitative
Interpretivist	Socially constructed, subjective, may change, multiple	Subjective meanings and social phenomena. Focus upon the details of situation, a reality behind these details, subjective meanings motivating actions	Research is value bound, the researcher is part of what is being researched, cannot be separated and so will be subjective	Small samples, in-depth investigations, qualitative
Pragmatism	External, multiple, view chosen to best enable answering of research question	Either or both observable phenomena and subjective meanings can provide acceptable knowledge dependent upon the research question. Focus on practical applied research, integrating different perspectives to help interpret the data	Values play a large role in interpreting results, the researcher adopting both objective and subjective points of view	Mixed or multiple method designs, quantitative and qualitative

Although using the mixed-methods approach can enrich the data collection, the researcher initially must focus on the research question, purpose, and context (Creswell, 2009; Myers and Klein, 2011; Venkatesh et al., 2013). There are four types of mixed-method paradigm, namely triangulation, embedded, explanatory, and exploratory (Creswell and Clark, 2007) (see Table 3.2).

Table 3.2. Types of mixed-method research (Creswell and Clark, 2007)

Mixed-method Type	Description of usage
Triangulation	through merging qualitative and quantitative data to understand a research problem
Embedded	through using either quantitative or qualitative data to answer a research question within a largely qualitative or quantitative study
Explanatory	through using qualitative data to explain quantitative results
Exploratory	through collecting quantitative data to test and explain a relationship found in qualitative data

Venkatesh et al. (2013) summarised seven reasons for using mixed-methods (Creswell, 2009; Greene et al., 1989; Tashakkori and Teddlie, 2008) (see Table 3.3).

Table 3.3. Purposes of mixed-methods research (Venkatesh et al., 2013)

Reason of use	Description
Complementarity	Mixed-methods are used in order to gain complementary views about the same phenomena or relationships.
Completeness	Mixed-methods designs are used to make sure a complete picture of a phenomenon is obtained.
Developmental	Questions for one strand emerge from the inferences of a previous one (sequential mixed-methods), or one strand provides hypotheses to be tested in the next one.
Expansion	Mixed-methods are used in order to explain or expand upon the understanding obtained in a previous strand of a study.
Corroboration/Confirmation	Mixed-methods are used in order to assess the credibility of inferences obtained from one approach (strand).
Compensation	Mixed-methods enable compensating for the weaknesses of one approach by using the other.
Diversity	Mixed-methods are used with the hope of obtaining divergent views of the same phenomenon.

The motivations behind using the mixed-method were highlighted in the literature as it is able to address exploratory and confirmatory research simultaneously (Teddlie and

Tashakkori, 2009). Walsham (2006) highlighted that qualitative methods have been employed in social science studies for exploratory research with the aim of understanding a phenomenon and/or generating new theoretical insights. Other scholars have suggested that stronger inferences can be achieved when using mixed-methods paradigm than using a single method (Teddlie and Tashakkori, 2009). This point of view has been supported by Johnson and Turner (2003), who emphasised, as a result of their study, that mixed-methods research can strengthen both quantitative and qualitative methods and provide further insights into a phenomenon than each method when used individually. Moreover, mixed-method research paradigms can do the following:

1- Overcome the weaknesses of using single paradigm (qualitative or quantitative) by taking advantage of the strengths of both;
2- Provide stronger evidence for conclusions through convergence and corroboration of findings; and
3- Produce a more complete knowledge essential to informing theory and practice (Johnson and Onwuegbuzie, 2004).

Lastly, mixed-methods offers a larger assortment of contradictory and/or complementary findings to further improve the reliability of the study (Teddlie and Tashakkori, 2009).

The advantage of discussing contradictory findings is not limited to improving understanding the phenomena. Addressing contradictory findings helps to assess the study’s limitations or interrelations between its components, opening new opportunities for future investigation (Venkatesh et al., 2013). Complementary findings are equally valuable in providing a holistic view of a phenomenon and supplementary insight into relationships among the components of a study. Bryman (2006) has presented seven key motives to use a mixed-methods research paradigm (see Table 3.4).

Table 3.4. Motivations for using the mixed-method design (Bryman, 2006; p.82)

Reason of use	Description
Triangulation	Use of two or more independent sources of data or data collection methods to corroborate research findings within a study
Facilitation	Use of one data collection method or research strategy to aid research using another data collection method or research strategy within a study
Complementarity	Use of two or more research strategies in order that different aspects of an investigation can be dovetailed
Generality	Use of independent source of data to contextualise main study or use quantitative analysis to provide sense of relative importance
Aid interpretation	Use of qualitative data to help explain relationships between quantitative variables
Study different aspects	Quantitative to look at macro aspects and qualitative to look at micro aspects
Solving a puzzle	Use of an alternative data collection method when the initial method reveals unexplainable results or insufficient data

Creswell (2009) identified six research strategies within the mixed-method approach, namely sequential explanatory, sequential exploratory, sequential transformative, concurrent triangulation, concurrent nested, and concurrent transformative. These strategies have been summarised by Al Ahbabi (2016) (Table 3.5).

In this study, the most appropriate research paradigm was ‘pragmatism’ as helps in developing a comprehensive overview of various phenomena of interest that cannot be totally understood when using an independent method, such as qualitative or quantitative. Moreover, mixed-methods requires the use of both paradigms as it requires both subjective and objective points of view. The subjective view helps to identify factors that affect operator reliability as a result of the presence of “work stress”, and the objective view helps the researcher examine the influence and impact of these factors. In addition, the ability to integrate different perspectives can help in the collection and interpretation of the required data. For this reason, this research uses a pragmatist approach that reflects a practical and applied research philosophy.

Table 3.5. Mixed-methods strategies and their key features (Al Ahbabi, 2016, p.129)

Strategy	Implementation	Priority	Stage of integration	Use of theory
sequential explanatory	Quantitative followed by qualitative	Typically quantitative, but can be qualitative or equal	Interpretation phase	May be present
Sequential exploratory	Qualitative followed by quantitative	Typically qualitative, but can be quantitative or equal	Interpretation phase	May be present
Sequential transformative	Either quantitative followed by qualitative, or qualitative followed by quantitative	Quantitative, qualitative or equal	Interpretation phase	Definitely present (i.e. conceptual framework, advocacy, empowerment)
Concurrent triangulation	Concurrent collection of quantitative or qualitative data	Preferably qualitative, but can be quantitative	Interpretation phase or analysis phase	May be present
Concurrent embedded	Concurrent collection of quantitative or qualitative data	Quantitative or qualitative	Analysis phase	May be present
Concurrent transformative	Concurrent collection of quantitative or qualitative data	Quantitative, qualitative or equal	Typically analysis phase, but can be during interpretation phase	Definitely present (i.e. conceptual framework, advocacy, empowerment)

Hence, the mixed-methods approach has been applied in this research because it could help in highlighting plausible theoretical answers to the topic in question by providing assistance that overwhelms any practical or cognitive barriers associated with carrying out this particular type of research. Moreover, the combination of induction and deduction allows for abductive reasoning, which is required in this type of research. Lastly, this method enables the researcher to validate results by developing integrative types of finding. Since the strategy followed in this research involved addressing the qualitative data in an exploratory form followed by a confirmatory form to represent the quantitative set of data, the particular nature of the research questions in this study compel the implementation of the sequential exploratory mixed-methods strategy. The reason for selecting this strategy is that the researcher is required to ascertain the current organisational practices at the port that affect operator reliability during marine port pilotage operations. This process is qualitative in nature and will help in understanding and identifying the factors perceived as being prevalent in terms of importance to conceptualise a reliability index that can be used by decision-makers in order to predict daily operational practices. The quantitative data (as discussed in Chapter 4) was used in developing research tools to extend and validate the findings. Thus, by applying the qualitative data in order to expand on quantitative results, both methods were used.

3.5 Research tools and data collection

The way that a researcher collects the required data in order to meet the objectives of the research is defined as the research methodology (Ghauri and Gronhaug, 2005). The research methodology builds upon a systematic, focused, and orderly data collection process, which helps to answer the research questions and to achieve the research objectives. In this research, the process used combined both inductive and deductive reasoning. This choice was because the literature on the research subject confirmed a lack of theoretical, fragmented, and empirical knowledge on the topic. Therefore, this research began with an inductive reasoning approach followed by deductive reasoning. Moreover, a sequential exploratory mixed-methods strategy was chosen for this study. This strategy was represented by a qualitative data collection process in the first stage of the research (Chapter 3) by observing field operations, semi-structured focus group interviews, and an investigation of the accidents that had occurred at the selected port. This process is followed by a quantitative data analysis using different techniques, which is presented in Chapter 4.

3.5.1 Field observation

Observations are used to identify naturally occurring events in order to investigate field experience, represent social activities, and understand social processes within the acquired field. Since the literature does not provide an insight into the nature of the pilotage operation and the degree of interactions between various parties working there, the researcher has decided to use a suitable method that can provide an overview of how the operation is conducted, and identify the role and degree of importance of each participant in the marine pilotage operation. Therefore, observations are one of the qualitative techniques used in this research to gain a further understanding of the subject under investigation (Bryman, 2003). Moreover, observation was used amongst a group of workers to explore and generate organisational concepts and models (Steyaert and Bouwen, 2004). This method has been used widely across different fields of study, such as organisational ethnography (Rosen, 1991) and cognitive mapping (Brown, 1992). The researcher can use observation to complement findings obtained through other methods, such as interviews, to build an understanding of how daily operations are managed and conducted. Observation allows the researcher to investigate the day-to-day experiences and behaviour of subjects in a particular environment (Cassell and Symon, 2004).

Observation has two distinct categories, structured and unstructured. Structured observation is used to record physical activities and verbal behaviour, whereas unstructured observation is used to understand and interpret cultural behaviour (Mulhall, 2003). This investigation employed unstructured observation to understand the role of each participant and identify the degree of operational interactions between each operator in a highly dynamic operation. The researcher used this method to structure interactions between operators within an operation, which helped to identify the key parties in a real-world setting.

3.5.2 Focus-group semi-structured interview

One of the important steps in collecting data is the way in which the researcher interviews experts for their opinions. The interview is a common research practice and works as a primary means of gathering the required data to achieve research objectives. Cohen et al., (2013, p.351) have cited that,

> *"By providing access to what is 'inside a person's head', it makes it possible to measure what a person knows (knowledge or information), what a person likes or dislikes (value and preferences), and what a person thinks (attitude and beliefs)".*

The order of the interview may be controlled while still allowing room for spontaneity and the interviewer can press not only for complete answers, but also for responses to complex and deep issues. The interview approach varies as the topic of the investigation and the nature of the working environment under assessment varies too. Since this research starts by collecting qualitative data to support the quantitative processes in the next chapter, a focus-group semi-structured interview data collection process was employed. The main reason for choosing focus-group semi-structured interviews in this research is that it is ideally suited to exploring the complexity surrounding the reliability of operators who are subject to daily influences that affect their performance, behaviour, and attitude at work by encouraging participants to engage positively with the process of the research.

Rabiee (2004) described the focus-group interview technique as in-depth group interviews where participants involved are selected because they purposively form a part of a specific population, although they are not necessarily representative. The focus group is then given a specific topic to discuss. Moreover, focus group participants are chosen based on certain criteria, such as specialist knowledge of the topic in question, are within a specific age range, have similar demographic characteristics, and are comfortable discussing the topic and being interviewed with one another (Richardson and Rabiee, 2001). According to Burrows and Kendall (1997) the concept of applicability should be applied to this approach, as participants are selected because of their knowledge of the study area. It is worth mentioning that the group dynamic is one of the distinct features of this approach, and the type and range of generated data through the social interactions between experts are often deeper and richer compared to the data obtained in individual interviews (Rabiee, 2004).

The semi-structured interview offers an opportunity to probe, discuss answers in detail, and build on the interviewees' responses. In this research, a semi-structured interview protocol was followed and began with general questions about the topic and pilots' experiences in the organisation. The design of the semi-structured interviews enabled the researcher to ask open-ended questions that outline the criteria to be covered and was supported with a focus group that helped the pilots in making conversation and retelling experiences that might have been missed in an individual interview. Therefore, adopting focus-group semi-structured interviews serves as a valuable data collection method that helps meet the objectives of the study.

Accordingly, facilitating the semi-structured focus-group interviews is considered effective in allowing the participant to express freely their own opinions and experiences (Flick, 2014). The focus group helps further by providing a wide range of information, ideas, and feelings about existing issues, and highlighting the differences between participants' perspectives (Rabiee, 2004). Moreover, facilitating the semi-structured interviews aids in ensuring that the discussions between participants cover all areas of a topic (Silverman, 2014), while the focus-group process generates deeper data sets and richer information than those collected from individual participants (Rabiee, 2004).

3.5.3 Accident investigation

As part of the qualitative data collection process, the main aim of this section is to further the researcher's understanding of the current organisational standards applied in daily operational practices. Accident investigation adds valuable insight into the current phenomenon surrounding the operational practices that influence operator reliability. This approach makes vital contributions to this study by looking back on existing operational accidents to determine the facts surrounding the cause of an accident and identifying the contributory factors that led up to the event. In addition, accident investigation plays a fundamental role in meeting the objectives of this study and provides a clear overview of operational safety issues that imply urgent operational, managerial, and structural changes, in the form of regulatory levels, in order to improve future system safety and accident prevention through recommendations and corrective actions.

In this section, the researcher highlights four accidents that occurred during marine port pilotage operations at the port selected for study. Three of these events were from the selected port's accident investigation record, and one event occurred when the researcher was undertaking field observations. Moreover, the researcher was later involved in event investigation and addressing the main operational issues surrounded this operation by interviewing the key operational parties identified from the observation section. To summarise, the researcher has been able to identify a number of issues associated with marine pilotage operations.

3.6 Research process

In this section, the researcher explains the process followed in collecting the required data during port visits. This research aims to investigate the current working practices within the pilotage operations by conducting a case study in one of the busiest and strategically located ports in a particular Asian country. Duo to the security and confidentiality of this country's economy and operator security, any information that could lead to the identification of the operators or the location of the port is withheld. This port was selected because the researcher gained official access to some critical operational information. Moreover, this information has had a significant positive impact on the collection of the required data, contacting the participants easily, and accessing sensitive data that is often hidden from public due to governmental policies. This data is to remain anonymous during the process of this study to maintain the port's required confidentiality. The port's anonymity is maintained because port management has requested that the researcher does not release the name of this port nor release any information that could lead to identification of the port.

The selected port is considered as a hub-port to its country for two reasons. Firstly, the selected port is the only port in the country that can receive the majority of ships of different sizes, such as the Ro-Ro, container, tanker, passenger, bulk, and car carrier. Secondly, most of the cargo imported into that country first arrives through this port. According to the port statistics, over 55 million tonnes of cargo handling moved through this port in 2017. In addition, the International Association of Ports and Harbours (IAPH) placed the selected port within the top 40 of the World Port League in containerisation increment, and one of the top 5 in the area (IAPH, 2017). Furthermore, this port is located in a strategic location, as all of the ships crossing the area must pass close to that port, which means that the port is often used for shelter in cases of emergency. Accordingly, this port has been continuously increasing in size, infrastructure, and marine services over the last decade aiming to handle as many ship sizes and as much cargo tonnage as possible in limited time following effective operational standards.

Therefore, port management emphasises optimising the port's operational working procedures and practices to comply with international working practices in place. This study will help the management of that port to investigate in depth any deficiencies and provide the decision-makers with recommendations and operational tools to enhance operational reliability during pilotage operation, specifically focusing on a pilot as an essential part of the marine pilotage operation.

The following sections detail data collection, which began by contacting the port for approval.

3.6.1 Establishing port contact

The researcher contacted the port authority officially by sending an official letter addressed to the senior management. The letter contained researcher details, the research topics and objectives, the expected outcomes, and an offer of future operational support to aid management in enhancing the operational standards. The management replied with conditional approval and requested further formal clarification of items such as the targeted experts and the places that would be visited by the researcher. This information was required by the Port State Control (PSC) and the Maritime Coast Guard Agency (MCGA) of the country in order to issue the access permit. The researcher gained a permit to access the port for three months, which started from July 2017 and ran until September of the same year.

3.6.2 Obtaining port operational documents

The researcher approached the management of the marine operation department and introduced himself, the nature of the study, and its main objectives. This step was important, as the researcher was able to make a positive first impression on management. The management then offered support to the researcher and direct contact if any problem emerged or clarification was needed during the research process. This contact allows the researcher to access almost-confidential port accident statistics, operational policies and procedures, access on board the arriving ships, and the arrangement of meetings with all parties involved in pilotage operations to conduct focus-group semi-structured interviews and review port operational plans that are in place. This section highlights the internal policies, regulations, and standards related to operations and compares them with the real working situation at the port by analysing the port's accident data analysis, carrying out field observations on ships under pilotage command, and considering interview comments.

3.6.2.1 Port operational procedures

The most essential part of every organisation is setting organisational goals and visions. For this selected port, visions, goals, and standards are clearly stipulated and written, well maintained, and updated to adhere to international maritime recommendations and standards. Through a literature review, and due to the nature of the marine pilotage operation, which is characterised as highly dynamic and more practical than theoretical, there is no evidence of who is involved in the pilotage operation, particularly at the front line of the operation. However, the only identified operators within the literature were the pilot and vessel traffic service (VTS) from the port's side (Mokhtari et al., 2012; Praetorius et al., 2015), and the shipmaster (Trucco et al., 2008) on the other side without identifying other involved parties such as the tug master, and the harbour master. Thus, this research highlight the key factors involved in the operation to identify the degree of influence among them. Due to time constrains, the research will focus on the marine pilot as an essential driver of the operation, and how the pilot is the first priority during an operation.

3.6.2.2 Port pilotage operational policies and standards

In 1968, the IMO recognises the significance of employing qualified pilots in port approaches and other areas where the local knowledge is required when the organisation adopts assembly resolution A.159 (ES.IV), "recommendation on pilotage". This resolution recommends that the government enhance pilotage services by defining the most appropriate safety measures as well as defining the ships and classes of ships mandatory to be piloted by an official designated pilot. Accordingly, in 2004, the resolution A.960 (23) adopted by the IMO encouraged pilotage authorities to provide marine pilots with regular effective training, certifications, and operational procedures. The IMO has recognised the significant role that the pilots play in promoting maritime safety and protecting the environment. Therefore, port authorities have both statutory and non-statutory powers, which allow the port authority to state the minimum requirements and qualifications needed to assign a person for berthing and un-berthing ships and ensuring port safety. In sum, there are no international standards when employing a pilot to conduct pilotage services at a port, as the discretion remains based on port authority requirements.

However, in this study, the port under investigation regulates the pilotage operations as compulsory for all ships that use the port at any time for any reason. There were exemptions for certain types of ships, which are the following:

1- War ships that belong to that country;
2- Governmental ships designated for non-commercial purposes;
3- Ships with a gross registered tonnage (GRT) lower than 150 GRTs;
4- Yachts and boats designed for entertaining;
5- Port units used for port services, such as tugs, pilot boats, floating cranes; and
6- Ships with a certificate of pilotage exemption granted by the port authority, such as bunker barges.

The port authority, in regulating the pilotage operation, has placed certain requirements on qualified pilots. Any pilot assigned to conducting a pilotage service is selected based on the ship tonnage, specification, and types. It is the responsibility of the port authority to provide the operators with all required training, regulatory policies, and the proper equipment for the operation.

The pilot gains experience over time and is subsequently placed in the pilot ranking system. Four pilot ranks are used based on the requirement of the chosen port, as shown in Table 3.6.

Table 3.6. Marine port pilot ranking system

Rank	Definition
Trainee pilot	Has attended and successfully accomplished classes on pilotage training conducted at an accredited institute by the port authority and has conducted a practical pilotage operation with an experienced first-degree pilot on ships with limited tonnages for a certain period of time.
Third-degree pilot	Has successfully accomplished practical pilotage training and the on board, written, and oral exams. The pilot with this rank is allowed to pilot ships with no more than 8000 GRTs.
Second-degree pilot	Has successfully passed the written, practical, and oral exam designed to examine pilot's eligibility to be promoted from third-grade. The total tonnage permissible for pilotage at this rank is limited at 16000 GRTs'.
First-degree pilot	Is eligible to conduct pilotage services on all ship types with unlimited tonnages.

The selection of a pilot to conduct the pilotage operation is based on the decision of the duty harbour master. The duty harbour master is an experienced first-degree pilot with experience in pilotage operation of more than 10 years at this level and is usually assigned by the port authority. The responsibilities of the harbour master are as follows:

1- Assure navigational safety within port limits and inside navigational channels;

2- Monitor all navigational movement inside and outside of the port;

3- Supervise the VTS operations;

4- Update local and Admiralty navigational charts;

5- To check and assure the proper function and working conditions of all the navigational equipment used for monitoring ships' movements;

6- To check and assure the proper function of the communication equipment and channels; and

7- Supervise issuing fines, maintenance permissions, and accident investigations.

The harbour master, due to the nature of his/her daily operation, must be aware of any pilot’s limitations on their ability to conduct the operation. The selection process for the harbour master is subject to either the pilotage service history or subject to a present daily situation. For instance, if the harbour master is aware that a first-degree pilot is stressed due to external factors, then the harbour master is obligated to ensure the safety of navigation and must choose another qualified pilot who is capable of handling the approaching and leaving ships.

3.6.3 Compiling interview groups

To conduct effective interviews, the researcher developed a general overview of how the operation runs, as highlighted on Section 3.7.1. The main objectives behind this process are as follows:

1- to identify the key operators involved at the front line of marine port pilotage operation;

2- to identify the link between those operators; and

3- to identify the role of each operator at each operational stage.

Moreover, the literature review was facilitated to offer interview guidance. This step helps to form a set of questions to structure the interviews and generate effective discussion points. In addition, the researcher facilitated the interview by forming participant groups. Accordingly, this study was conducted in semi-structured focus-group interviews.

Conducting semi-structured interviews requires the interviewer to establish a general approach by deciding what topics or grounds are to be covered and, which questions need to be asked (Drever, 1995). The nature of the questions was open-ended and was guided by general questions to allow the respondent to respond freely and comfortably.

The researcher collaborated with the marine department to organise a participant group, arrange a time, and place for the interviews. The head of the marine department encouraged pilots to participate in this research and followed up with notices to ensure their participation. Using this approach, 35 marine pilots were recruited to participate in this investigation. These pilots worked different shifts and had different ranks and levels of work experience (see Table 3.7).

Since this study focuses on the pilot as the key factor in conducting marine pilotage operations, the participants selected were pilots. No exclusions were applied to the sample, other than that participants be field pilots at the port.

Table 3.7. Pilot demographic summary

Expert characteristics		Frequency (N=35)					
		Participant Qualification/category					
		Dip. +PL	3rd +PL	2nd +PL	1st +PL	Master +PL	Total (%)
1. Gender	Male	19	3	7	0	6	**35 (100%)**
	Female	0	0	0	0	0	**0 (0%)**
Total		**19 (54%)**	**3 (9%)**	**7 (20%)**	**0 (0%)**	**6 (17%)**	**35 (100%)**
2. Age Group	20- 29	8	1	0	0	0	**9 (**25.7%)
	30 – 39	3	2	2	0	1	**8 (**22.9%)
	40 – 49	3	0	3	0	2	**8 (**22.9%)
	50 – 59	5	0	2	0	2	**9 (**25.7%)
	60 and above	0	0	0	0	1	**1 (**2.8%)
Total		**19 (54%)**	**3 (9%)**	**7 (20%)**	**0 (0%)**	**6 (17%)**	**35 (100%)**
3. Pilot's Rank	Trainee Pilot	0	0	1	0	1	**2 (**6%)
	Third Pilot	4	1	0	0	0	**5 (**14%)
	Second Pilot	3	2	1	0	0	**6 (**17%)
	First Pilot	12	0	5	0	5	**22 (**63%)
Total		**19 (54%)**	**3 (9%)**	**7 (20%)**	**0 (0%)**	**6 (17%)**	**35 (100%)**
4. Pilotage Experience	≤ 5 Years	8	0	2	0	1	**11 (**31%)
	6 – 10 Years	3	3	0	0	2	**8 (**23%)
	11 – 15 Years	0	0	1	0	1	**2 (**6%)
	16 – 20 Years	0	0	1	0	0	**1 (**3%)
	> 20 Years	8	0	3	0	2	**13 (**37%)
Total		**19 (54%)**	**3 (9%)**	**7 (20%)**	**0 (0%)**	**6 (17%)**	**35 (100%)**

The first demographic characteristic is the pilots' age groups. The balance between participants' numbers per each different age group can be observed. This might help to balance the answers in accordance with the expert's experience and position. The youngest and most senior pilots represent the age groups of 20-29 and 50-59 make up 26 % each of the participant group. Pilots of age 30-39 and 40-49 make up 23 % each of participants. These age differences will help in obtaining a wide range of perspectives.

The second demographic characteristic is pilot ranking. 63% of the participants of this study are first-grade pilots. This percentage will add value to the results, as first-grade pilots are required to have over 10 years' experience of pilotage, which will aid them in providing accurate perceptions and responses. 6, 5, and 2 % of the participants were second-grade, third-grade, and trainee-level pilots, respectively. These percentages allow for the maximum possible amount of information to come from experienced, senior pilots, while also allowing junior pilots to express their opinions.

The above variance has valuable outputs, since almost two thirds of the participants were senior pilots. The seniority of those participants can complement the answers given by the lower ranked participants through the group interviews. For this reason, a focus-group interview was chosen as it is proven to be effective at eliciting feelings, stories, and other aspects of an individual's experiences, as highlighted by Flick (2014), Rabiee (2004), and Silverman (2014).

Participant selection was purposive since they are selected for their particular characteristics that will aid in understanding and exploring central criteria of the acquired phenomenon (Ritchie et al., 2013). The two reasons for selecting purposive groups are highlighted by Ritchie et al. (2013):

1- to ensure that all the key operational features relevant to the subject are covered; and

2- to ensure that, within each of the identified key criteria, diversity is included so that the impact of the characteristic concerned is explored.

For instance, work experience is a common criterion and is used to ensure that any differences in operational perspectives can be identified. Accordingly, this research focuses only on assessing the port marine pilot in order to provide a picture of the current operational phenomenon, which forms a homogeneous group as it represents only marine port pilots. In contrast, the selected group is varied in its internal characteristics such as operator's age range and working experience. This aims to identify central criteria that are prevalent across a range of operators (Ritchie et al., 2013).Thirteen questions were used in conducting and directing these interviews.

However, these questions were used by the researcher to open discussions and allow interviewees to tell their own stories and discuss with their different points of view. Moreover, the researcher might identify more factors present within the working practices that were not identified in the literature reviews.

The selected questions were tested through a pilot study aiming to ensure the cohesiveness and clarity of the given questions. These questions were sent to five senior pilots who had a considerable amount of experience as a pilot. These pilots' suggestions were considered and incorporated into the amended version of the questionnaire, to simplify and ease the selected terminology. This process is considered essential and allows the expert to understand the given questions and reply without confusion. Although the researcher gained considerable support from the literature in developing an overall picture of the topic under investigation and identifying a research gap, it is highly essential that the researcher does not direct interviews based on the literature. In other words, the researcher can use the identified questions to open a discussion about the topic and let interviewees tell their own story with other colleagues for further discussion and knowledge sharing. This step has significant outcomes for the research result and can reduce the existence of research bias and eliminate any pre-conditioned answers (Abdelrahman et al., 2011). Moreover, the researcher has conducted a confirmatory test using the Delphi method in Chapter 4 to test the agreements among the examined pilots in terms of the factors identified in this chapter. This step forms the quantitative component of this study. The researcher used the comments and suggestions returned by the officials from the pilot study to refine questions for the actual study.

Before conducting the interviews, the researcher informed interviewees that the information of the participants will remain anonymous, and the written results will not be indicative of the identities of any of them. Moreover, the interviewees were informed that the process would be recorded to allow the researcher to return to the script and consider revising pilots' answers to avoid missing any useful information. Participants were also informed that the recordings would be kept private to ensure their anonymity. Accordingly, each group was asked to confirm their approval of the interview being recorded for the aforementioned reason by signing the consent form. According to Walsham (2006), recording the interviews is useful and can help in providing the investigator with full and detailed descriptions of what the interviewees said. The interviews were conducted in the local language used at this port to ensure overcoming any language difficulties that could hinder the research process. The recordings were then transcribed by the researcher and translated into English.

The researcher checked the translated transcriptions with a bilingual language speaker who is a native speaker of the two language. This person has lived since birth and studied in the country where this investigation took place for more than 18 years and moved to the UK to obtain a degree and work as a senior officer in a commercial company for over 20 years. Moreover, this speaker has held both nationalities since birth, the UK and the nationality of that country where this study was conducted. Accordingly, the researcher received constructive comments, and some aspects of the translation were amended. The researcher assured the participants of their confidentiality and privacy, as their information, as well as the name of the port and country, will not be revealed to any third parties for privacy and economic security purposes. The interviews took place in the pilotage main building where there was less navigational movement due to the full berth occupancy at that time. It was hard to ensure lesser movement, which forced the researcher to maintain direct contact with different departments on a daily basis and monitor the operational movements on that day. Moreover, this process was time-consuming, and arranging an interview that suited all pilots took nearly two months. During this period, the researcher spent time reading the port policy, accident reports, and making operational observations in order to conduct further investigations on board the ship during pilotage operations, which is discussed later in this chapter.

When the researcher had gained enough information from the pilots, he ended the interview by thanking all participants for their effort and added that he hoped to support the industry to implement new operational strategies if needed. The researcher ended the interviews when he noticed a repetition of given answers and agreement between pilots that all operational aspects were covered. At the end of the interview, the researcher expressed his sincere appreciation and thanked them all for their efforts. Furthermore, the researcher asked the participants for permission to contact them if any further details are required, and gained the approval. Pilots expressed their interest in the topic and ask the researcher to get a copy to them of the research results at the end of the study.

Those participants continued with their participation in this study across the following chapters and responded to the given questionnaires developed by the researcher. The interviewees were cooperative with the researcher. However, the participants felt that their support in terms of explaining the current study findings would help port management and decision-makers to introduce the necessary changes and improve current operational practices. Indeed, this interest may imply honest answers to the questions and feeling free to convey their perceptions and comments.

3.7 Field investigation and data collection

In this section, the researcher employed the proposed research tools highlighted in Section 3.5 to collect the required data. This section provides an overview of marine pilotage operation processes, followed by an interview with an expert and a discussion on the number of reported marine accidents occurring during pilotage operation.

3.7.1 Observing the pilotage operational process

The researcher has summarised his observations into the way that the operation was conducted, starting from the point at which the ship sends the information to the vessel traffic service (VTS), who represents the port to contact, monitor, and provide assistance to ships around and inside the port, until the ship is moored on the designated terminal (see Figure 3.2). It is essential to summarise the operation to identify the degree of interdependence between the key operational drivers and value the criticality of the operation. Since the main objective of a marine pilotage operation is to maintain the safety of ships navigating within a confined port area, cargoes, port equipment, and the marine environment, the criticality of the operator reliability is focused on in this research. The majority of marine accident investigations point to human error as the main cause of accidents during port pilotage operations.

The researcher observed 17 pilotage operations, 14 of which involved ships entering the port, and 3 involved ships leaving the port. The reason for observing these operations was to monitor the pilot while conducting the operation and to identify every reported order either to the shipmaster or to any other parties involved in the operation. Moreover, the researcher gained some useful insights that may help in assessing pilot reliability in the next chapter of this study. The researcher has summarised the operation through the following points:

3.7.1.1 Establishing organisational communication (EOC)

The first link starts with the Ship Operational Department (SOD) contacting the Port Operational Department (POD) to provide the required information to allocate the suitable jetty. This port requires the ship to provide the following:

1- Ship specification (type, length, draft, etc.);
2- Ship registration details (IMO number, flags, GRT, etc.);
3- Estimated Time of Arrival (ETA)
4- Last and next port of call
5- Cargo types (container, general, etc.)
6- Crew list
7- Agent details

The POD will then advise the harbour master (HM) to allocate the proper ship’s berth before arrival. Once the berth has been allocated, the POD grants permission to the SOD. Once this permission has been granted, the SOD confirms to the shipmaster (SM) the approval with further port details and requirements. The role of the POD is to arrange all facilities to ensure operational safety. The POD confirms the arrival and the specification of the ship with the HM in order to ensure a safe operation. The HM then confirms with the jetty operator (JO), who is responsible for arranging for cargo handlings, clearance of the jetty from any obstacles and termination of ship paperwork. In addition, the HM informs Vessel Traffic Services (VTS) with the above information provided by the SOD to the POD and the assigned marine pilot (MP) in order to conduct the operation.

3.7.1.2 Before arrival

According to the port regulation, it is mandatory to all ships calling at this port to report essential arrival information (i.e. ship's name, call sign, cargo types, ETA, etc.) to the VTS five, two, and one day(s) before arrival. Once received, it is the role of the VTS to confirm with the HM the details to make sure all safety requirements are met before arrival. This information is useful and allows the VTS operator to monitor ships' movement using one of the monitoring electronic navigational systems, such as Radar or AIS, that are available at the VTS station once the ship enters the range of these devices. Moreover, this system helps port management decide how to reschedule the entry in accordance with the current operational situation, if the reported ship is expected to be delayed or to have given false information for any reason.

3.7.1.3 Before arriving to the pilot station (PS)

Before the ship approaches the PS located on the outer gate of the port designed by the port authority in accordance with the international standards to pick the pilot from, the SM must get updated instruction and relevant navigational information from the VTS operator. The information includes current port navigational movement, readiness of pilots and tugs, navigational hazards, the tide, and the movements of the current. It is the role of the VTS operator to inform the MP and the tug master (TM) that the ship is arriving in order to prepare for the conducting of the operation. The MP must be informed of the operational details, such as the ETA, the terminal, and the shipside on the jetty, in order to arrange a time to embark the ship and the required tugs and prepare operational plans. The TM must be informed of similar information to plan for safe operations. A direct communication must be established and checked regularly with the VTS, SM, MP, and TM to ensure a clear order understanding and share any required operational information. Although the SM does not make direct contact with the TM by sending orders, a clear communication understanding must be maintained at all times during the operation. Moreover, the role of the HM is to supervise the operation to ensure the clarity of all orders, transparency of all navigational information, and maintenance of port operational standards. Once all parties are ready to conduct the operation, and the procedures have been agreed upon, the VTS operator will grant the SM permission to proceed at a safe speed towards the PS for the MP boarding process.

3.7.1.4 MP on board

The MP must identify himself to the SM, and the SM must present the pilot card. The pilot card contains important ship details, such as engine power, bow thruster power, and length of the ship that the MP must consider before conducting an operation to assess the manoeuvrability and make any necessary decisions. For instance, if the ship has a single screw right-handed propeller, this information is essential to the pilot in determining how to use the engine, as this decision leads to different movements to the aft side of the ship compared to the single screw left-handed propeller. Moreover, the SM must declare all available deficiencies present on a ship’s hull and machinery equipment to ensure safe operations. Any deliberate misleading or omission of defects incurs serious legal consequences. More importantly, the MP must be aware that his role is only to advise the SM by updating him or her with the required information on the operation, local regulations, and assist in solving any conflicts that might occur with any other parties. The SM must be aware that the control of the ship cannot be handed to the MP as he / she can question the MP on any decisions made. In addition, the MP must check during all operational stages that proper communication channels are maintained with all other involved parties in the pilotage operation. The MP must inform the VTS once arriving to the bridge, and the TM must be positioned in accordance with the designated point for pushing or pulling and attach the lines used for towage. The VTS must inform the MP of any navigational hazards appearing or changes during the operation. The MP must inform the TM of any action taking place in advance to avoid endangering the tug and its crew. These actions include use of the ship engine, thruster, course alteration, and the occurrence of any emergency, such as engine failure or loss of steering control. In addition, the TM must inform the MP of any changes that occur during the operation, such as the towing line being parted, to make the pilot aware and allow him or her take further action as required.

The role of the TM requires higher vigilance and to be cautious at all times supporting the MP and the SM when observing something that can affect the safety of the operation. It is essential that the MP is aware about the ability of the TM and the nature of the tug, limitations, capabilities, and how they can be operated to give feasible orders in order to ensure the safety of the operation at all operational stages. In addition, the language used during the operation must be in English at all times in compliance with port operational policies and standards. It is the port’s policy that all operators be capable of communicating in English. Moreover, using the local language and making small talk during the operation is not permissible at any time. The role of the JO is limited in terms of providing the pilot with information related to the position of the ship on the jetty.

3.7.1.5 Ship alongside the jetty

When the operation has been accomplished and the ship is alongside the jetty, the tug masters have to maintain their position until the MP ensures that all shore lines are made and the ship secured. Moreover, the MP must remain on board until this process is completed and report to the VTS with the time that the ship is alongside and secured. At this point, the MP can request the tug master to cast off the lines and leave towards the service jetties.

By referring to operational procedures, the author built a diagram (Figure 3.2) that shows operational processes between the main parties involved in marine pilotage operations. The number on each arrow represents the threshold point of operational process and information flow sequences between involved parties when conducting pilotage operations. Moreover, Figure 3.3 illustrates the hierarchy developed based on the operational observation, the standards followed by the port authority and highlighted by Alderton and Saieva (2013), for the main parties involved in marine pilotage operations.

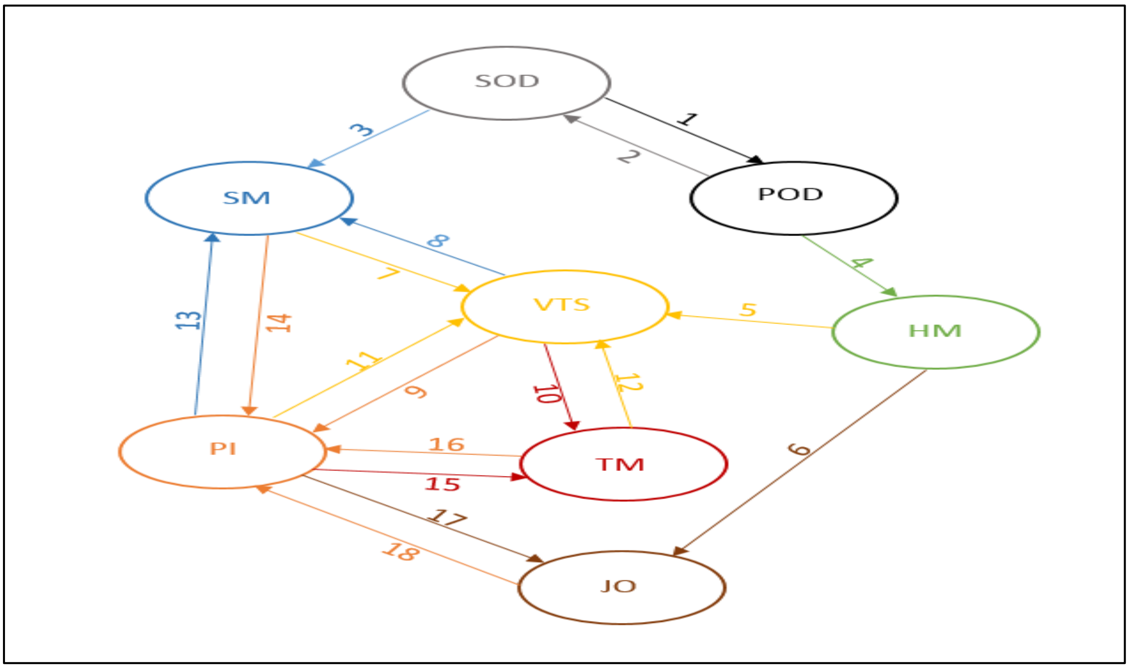

Figure 3.2. The main parties involved in marine pilotage operations

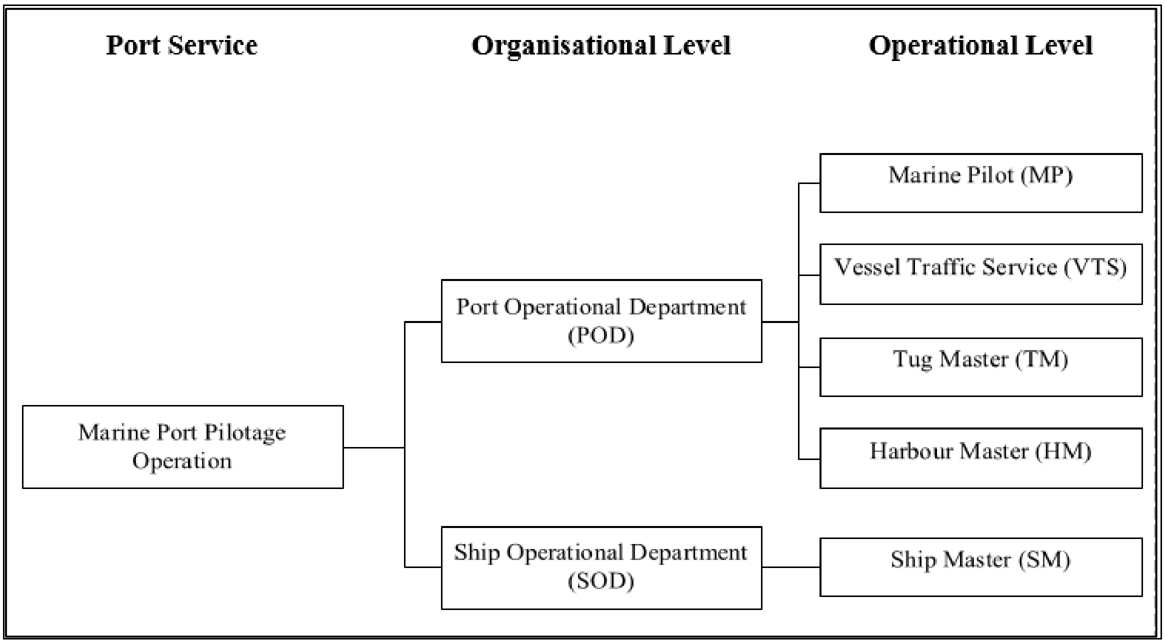

Figure 3.3. A hierarchy structure for the main parties involved in pilotage operations (Alderton and Saieva, 2013)

3.7.1.6 Researcher's observational comments

The researcher conducted observation of 17 pilotage operations, 14 arrivals, and 3 departure ships aiming to observe the actions taken by those central to the operation. The preconditions of the 17 operations conducted are briefly outlined as follows.

- Nature of the operations:
  - 14 entry operations (12 morning movements + 2 evening movements);
  - 3 departure operations (morning movements);
- Weather and sea conditions:
  - Extremely hot weather in the morning;
  - High levels of humidity both at night and in the morning;
  - Wind speed fluctuating from 0 to 20 knots;
  - Sea current ranging from 5 to 15 knots;
  - Wave and swell ranging from 0 to 5 on Beaufert scale (see Table 3.8)
- Ship types:

- 11 operations conducted on container carrier with sizes ranging from 50 to 102 K GRT;
- 6 operations conducted on bulk carrier with sizes ranging from 40 to 50 K GRT;

- Location of the terminal:
  - 8 operations on the south jetties;
  - 9 operations on the new terminals located at the north jetties;
- Duration of the operation:
  - Entry operations: From the pilot station, 1 hour to the south jetty and 50 minutes to the north jetty;
  - Departure operations: From the south jetty, 35–45 minutes to the pilot station, and from the north jetty, 25–35 minutes to the pilot station.
- All operations conducted with the support of two tugs

Table 3.8. Beaufort number scale (Ramin, 2010)

Beaufort Number	Sea Conditions
0	Flat
1	Ripples without crests
2	Small wavelets
3	Large wavelets
4	Small wave
5	Moderate (1.2m) longer waves. Some foam and spray
6	Large wave with foam crests and some spray
7	Sea heaps up and foam begins to be blown in steaks in wind direction
8	Moderately high waves with breaking crests forming spindrift
9	High waves (6-7m) with dense foam
10	Very high waves

The central parties in the pilotage service are the pilot and shipmaster. All other parties are important to the operation and take actions when ordered to. The first of these is the tug master, but the VTS operator and harbour master also play key roles. One of the main objectives of this observational process is to monitor the development of human error during pilotage operations and compare the results with those of the data collection from other sources, namely the interview and accident analysis. The researcher collected the following observations:

1- The shipmaster gave control of the entire operation to the pilot, who gave orders to the tug master, the shipmaster, and the helmsman without being challenged by any other operator. Although it is not obligatory that the shipmaster challenge the pilot's orders, on five instances, the pilot exceeded the speed limit, which resulted in fines for both him and the SM. In addition, on a further two instances, the ship got very close to the jetty, which required the pilot to put the engine on full power. Finally, there was another instance where the towing lines were parted, because the pilot ordered the tug master to pull at full power. It is key to note that all discussions made between the pilot and tug master were conducted in the local language.
2- The pilot did not always ask for the pilot card, which contains essential information.
3- The pilot did not use any electronic navigational devices, such as the radar.
4- The pilot did not always report to the tug master with any changes, such as using the engine or bow thruster.
5- The pilot was complaining about the performance of the tug master for not following orders.
6- The pilot embarked the ship after the ship had entered into the channel, which is not allowed by port regulation. Moreover, the pilot disembarked the ship at or just after the inner gate and before arriving at the pilot station, which is located after the outer gate.
7- Orders made to the tug for pulling and pushing next to the jetty were considerable in number, which increasingly irritated the tug master and put an immense amount of pressure on him. Moreover, these orders were made because the ship was

approaching very quickly to the jetty as the pilot delayed conveying orders to the tug master to stop pushing and to the shipmaster to stop the engine.

8- Neither the harbour master nor the VTS operator stopped the pilot and the tug master when they communicated using the local language.

9- Other parties involved in the operation must be interviewed to identify the degree of conflict, since the pilot complained about the performance of the tug master, the VTS operator never challenged the pilot on ship speed, and the harbour master never discussed the rules that were breached by the pilot during the operation. However, this study focuses only on pilot reliability, and due to the time constraints, other factors involved in pilotage are suggested for further study.

3.7.2 Interview data analysis

Analysing the collected interview data is a vital, but difficult, component of qualitative research (Braun and Clarke, 2006). According to Ary et al. (2018), when analysing qualitative data, the researcher must follow three main phases in handling the data: (1) organising and familiarising; (2) coding and reducing; and (3) interpreting and representing. The researcher, before analysing the collected data, is encouraged to read and reread notes taken from the interviews and organise comments made by respondents on the questions and sub-questions. This process allows the researcher to identify the main concepts expressed by the group of interviewees, categorise their concerns, and develop research criteria accordingly. The researcher will then be able to reduce the data and codify identifiable criteria and categories to interpret data and report findings.

It was suggested by Abdelrahman (2013) that, when writing up a thematic study, a researcher is required to describe and discuss each central criterion by offering examples from the data and using quotes to facilitate criterion characterisation. However, it is not necessary for the researcher to refer to every constituent identifiable code within each criterion, particularly when handling descriptive code (King and Harrocks, 2010). The researcher must concentrate on the robust and effective codes that illustrate and address criteria and answer the research questions (King and Harrocks, 2010). Similarly, Braun and Clarke (2006) have argued that the aim of the thematic approach is not merely a descriptive summary of the identifiable criterion, but also useful in developing a narrative that informs the reader of the process of the research findings in terms of the phenomenon that is under investigation. In addition, others have pointed to the significance of using direct, short quotes given by participants in order to allow for comprehension of particular points of interpretation made by the researcher (Symon and Cassell, 2012).

This section presents the data collected from the interviews conducted with the three groups of marine pilots working on a daily basis at marine ports. The aim of this process is to elicit a qualitative set of data underlining the nature of the operations by allowing the pilots involved in the process the chance to express their feelings and experiences freely. Since the main objective of this study is to identify factors that influence the reliability of an MP as the main driver in the marine port pilotage operation, this section aims to highlight these factors in depth. With the support of existing literature, the researcher must open general discussions relevant to the operation. As such, the researcher has initially prepared 13 questions that cover the main features required for maintaining operators that are more reliable. Moreover, these questions ask “why” and “how” and are open-ended in nature. The objective of these questions was to gain in-depth insight into pilot’s experiences and beliefs.

Semi-structured focus group interviews were conducted to develop a reliability model that can be used to assess the reliability of operators on a daily basis. Section 3.7.1 highlights that the main operators are directly involved in front level operations (see Figure 3.3). Moreover, those operators are subject to internal and external factors that could adversely affect their ability to conduct safe operations. Internal factors include personal willingness to learn something new or personal characteristics. External factors include stress due to the impact of the external environment. Through a comprehensive literature review, a lack in studies investigating the reliability of a human in the maritime sector was determined. Other industries investigated the issue by considering factors independently. The majority of these studies, for instance, focus on developing operator’s non-technical skills rather considering a holistic approach and considering other factors in conjunction with the requirements to maintain a higher operational reliability level. In this research, the developed model aims to overcome this issue by developing a holistic model based on the perceptions of pilots followed by identifying the degree of interdependence between these factors.

The following sections discuss the dimensions that conceptualise the framework of this study.

3.7.2.1 Operator Technical Proficiency (OTP)

According to the IMO, Resolution A. 960 (2004), operators conducting a pilotage operation are required to have specialised work-related knowledge and experience in the field of pilotage operations. It is the obligation of the competent pilotage authority to encourage the establishment of an adequate pilotage system within a port by assessing and maintaining the pilot’s qualifications with the support of additional specific training, which enhances the pilot’s work-related experience.

According to the interview discussions, three sub-criteria were identified under the main criterion, namely competencies including pilotage licensing, training courses, and pilotage experience.

- ***Competencies and Licensing (OTP-CL)***

A qualified operator has a set of competencies, licences, and certifications that exhibit his/her achievements in compliance with the minimum work-related knowledge essential for carrying out certain duties. These competencies cannot be achieved if not accompanied by training, knowledge of the nature of the operation, and a certain level of work experience. Therefore, a competent pilotage authority must ensure that the pilot holds an approved pilotage certificate, a licence recognised by the authority, and fulfilment of the minimum operational standards (IMPA, 2004).

In terms of competency and licensing, participants highlighted the importance of qualifications in developing their operational practices. Each pilot was asked about his certification (see Table 3.7). The pilots recognised the significant role that certification plays in their daily life. The majority of participating pilots stated that,

> *"The maritime industry requires higher levels of operational, policy, and safety knowledge, which are a result of years of experience and training"*.

Another pilot commented that,

> *"We are assigned as pilot after accomplishing a maritime diploma course provided by the port authority and getting certified. Some of our colleagues have higher degrees or certificate of competencies. However, higher certificate must be attached to the years of pilotage experience in accordance with the port system of pilotage ranking"*.

Pilots gave varying answers as to whether certification was important in enhancing pilot reliability. Some pilots stated that,

> *"Although some pilots with master licences came from shipping industries with prolonged maritime experience, pilotage requires very specific skills. Having a higher certificate of competency helps for better operational adaptation. We observed those*

> *who came with maritime background as having better working practices, as they adapt a lot more quickly than those with lower certification or no maritime background".*

The majority of pilots agreed that,

> *"We deal with many ships daily, the better and higher the certification, the better we do at understanding crew and ship behaviour".*

Three groups of interviewees revealed that there is no stipulated system within the port to ensure the validity of the pilots' certificates. The pilots are interested in improving their ability and knowledge through training courses and workshops. However, due to managerial process and procedures they are not able to improve further unless they decide to enrol in a private academy or course.

The majority of the pilots agreed on the significance of certification, licensing, and knowledge in maintaining their ability to conduct operations at more reliable standards, and stated that,

> *"Gaining operational knowledge from a well-recognised maritime academy and getting certified will add valuable expertise enabling us to handle different operational situations and crises more professionally in accordance with maritime standards. This certification also helps us be respected across the industry".*

Moreover, these pilots stated that their ability and reliability cannot be built only through certification. Certification must be supported by different operational skills, either managerial or personal. The pilot must improve his knowledge, not only in classes, but also through work experience.

- ***Training Courses (OTP-TC)***

During the discussions, the pilots pointed to training several times as a significant factor that shaped operator reliability. According to Alvarenga et al. (2014), training has been identified as one of the most dominant factors in organisational performance. A lack of training within the maritime sector has been found to be a prominent cause of accidents (House, 2007). Training courses might include a set of compulsory or additional operational requirements (Riahi et al., 2013). As human error accounts for 80% of maritime accidents, the International Maritime Organisation (IMO) has implemented the International Safety Management (ISM) code in 2008 (Berg, 2013). This code addresses the issue of human error by emphasising the significant role that operator training and education can play in ensuring operational performance safety. Therefore, implementing effective training on top of having suitable certification and experience was the aim of the ISM code in order to reduce the probability of human error during maritime operations (Berg, 2013).

This portion of the interview concentrates questions on how training can help improve operators' skills and to what extent training can complement pilots' certificates in maintaining higher operator reliability.

A senior pilot stated that,

> *"Training helps in shaping our operational procedures, learn about new technology, and adapt our personal behaviour towards safe working practices. Personal skills must be accompanied with proper, high quality training courses and our up-to-date licence".*

All of the pilots at this port agreed with this statement. The pilots pointed to the significance of training courses on their daily operational standards and stated that,

> *"We consider training courses the most dominant factor in shaping our operational performance, since training provides us with valuable knowledge and practical experience that help us adapt our beliefs and behaviour to daily operations".*

However, when asked about regular training, one of the pilots stated that,

> *"We are having difficulties in completing required training that we had before obtaining our pilot licences in order to cope with the new international standards that*

> *are recommended by pilotage international bodies. We frequently urge the management to organise training programmes".*

Other pilots have stated that,

> *"We consider training courses much more important than the certification. The training provides us with valuable knowledge and practical experience. These details we can use in our daily operations".*

The implications of having no training courses can be seen in the following statement:

> *"We need training courses that are related to our operation, as they allow us to feel important within the organisation. Training also prevents us from getting bored by refreshing our knowledge with new ideas and operating styles".*

Another pilot stated that,

> *"I believe there have been massive improvements in the maritime industry, and sometime I feel that I just drive a hunk of metal without understanding my actions and the consequences of these actions".*

This statement was justified by another pilot, as many juniors and senior pilots stated that,

> *"Special training courses help us improve our personal thinking skills, personal management styles, and teamwork buildings skills, which enable us to manage operations even when we are under stress".*

Another pilot offered further clarification:

> *"We face huge operational stress from management, the shipmaster, and due to the nature of the operations. Each pilot has different characteristics and operational style for dealing with this stress effectively".*

Therefore, one important criterion developed here was operational stress and how it relates to management involvement, which is discussed on section 3.7.2.2.

- ***Pilotage Experience (OPT-PE)***

Experience is obtained over years through a pilot conducting different types of ship handling operations, training courses, or the sharing personal pilotage experience. Practical experience has a huge impact on operator reliability and operational safety. One pilot stated that,

> *"Work experience has a huge impact on our daily operations. We learn from past personal or shared experiences, through training that we have received, and during our preparation for becoming certified pilots".*

A number of pilots agreed with this statement and argued that,

> *"We learn everyday differently, each pilot has experienced different operational demands, since every operation is subject to different parties and problems".*

This statement has been confirmed, since maritime operations are considered dynamic and subject to different circumstances every day. The dynamic nature of the operation adds extra stress to the pilot to learn and share experiences. One pilot stated that,

> *"We learn from one another. Other pilots can face different types of ships with different operational characteristics and particular handling skills. We might not be subject to any problems for a long time but maybe we will experience handling difficulties due to variations of the crew's mentality and equipment defects, which add stress to the pilot in implementing new operational strategies to ensure operational safety".*

In this research, participants have a wide range of experience of pilotage operations, which provides useful inputs to this research and highlight what is required in order to evaluate pilot's reliability. Maritime operations demand and require special training, seminars, and lectures to share knowledge and understand the nature of the other operators involved in the pilotage operation. All pilots confirmed the significant role of work experience in a pilot's operational reliability. A general statement agreed upon by all participants was that,

> *"Work experience adds valuable skills to operators and enables the pilot to conduct pilotage services within different working environments that provoke stress. Work experience can add something that colleges cannot provide us with".*

In addition, some of the pilots at this port consider work experience much more important than certification and training. However, some other pilots stated that,

> *"Work experience cannot compensate for the training and qualifications in terms of a pilot's personal reliability. They all work adjacently to each other, as the training courses are developed based on working experience, and working experience is taught on the training courses".*

Other pilots have stated that,

> *"We gain experience over time and learn different operational skills. However, current operational improvements require us to have higher certificate and training that can shape our skills and reliability. Work experience must build on the right upon our skills obtained in training courses and qualifications that are recognised worldwide".*

It is apparent from the above responses that work experience can be shaped through training, obtaining higher qualifications, and sharing knowledge and personal development. Pilots have stated that work experience is the most important factor in maintaining reliability in terms of personal qualification and personal training.

3.7.2.2 Operator fatigue (OF)

Fatigue was defined by Yule and Brown (2012, p. 47) as "a state of sleepiness characterized by feeling drowsy or tired that results in a reduced ability to maintain concentration, make decisions, and carry out skilled tasks". The word "fatigue" describes the workers' feelings of tiredness and depression, either mentally or physically (Kim et al., 2009). A fatigued operator is usually unable to keep working at the required level due to a lack of energy and motivation. As a result, forgetfulness and loss of memory or the ability to think clearly will happen for a short or extended time (Kim et al., 2009). Thus, a review of the current status of safety within the maritime industry and the human influence on operations indicated that fatigue was one of the most dominant factors in adversely influencing overall operational safety performance (Hetherington et al., 2006). Three criteria were identified to have a significant influence on fatigue, namely working hours and, operational stress, and working environment.

- ***Working Hours (OF-WH)***

There are two factors that were discussed in distinguishing the effect of working hours on pilot reliability. One senior pilot states that,

> *"We work in an environment that is incredibly physically demanding. We are subject to many factors that affect our reliability. One of them is the working hours in conducting pilotage services. Our working hours affect not only the number of hours we spend at work, but also our leisure time during the rest of the day".*

Many pilots agreed upon the importance of working hours in operator reliability. The majority of pilots have agreed that,

> *"Working stress during the night shift increases, as the required level of pilot vigilance in monitoring all unusual navigational hazards at night increases. This can add lots of pressures to pilots' mental demands. In contrast, when working in the day, pilots are subject to direct sunlight, which may also have an adverse effect".*

All pilots, who confirmed the significance of training and work experience of a pilot in managing these factors more efficiently, agreed with the above statement. Moreover, the second factor was also highlighted by pilots, who stated that,

> *"Working two 12-hour days might not harm the pilot reliability unless he has been asked to cover the shift of an absent pilot, has health issues, or is a more senior pilot who requires more rest hours than younger pilots".*

The nature of the operation requires pilots to work on shifts similarly to many other industries. The pilotage services at this port provide the service 24/7, even during public and national holidays. The operators work in a pattern of 2 days on duty followed by 2 days off duty. Each day on duty has an operation of a continuous 12 hours per day. This schedule means that the pilot works for 24 hours followed by 48 hours of rest.

This pattern was confirmed by the majority of pilots. However, some of the pilots stated that,

> *"Although I'm familiar with shift patterns, I feel stressed if it's changed, or if I've been asked to cover the shift of a colleague. I work at night and I like this shift, but during my working experience, I'm always tired because working at night requires higher operational vigilance than in the morning. This means I'm a lot more stressed as I am getting older. Also, I'm stressed because of changes made by management because of the implementation of new work demands without supporting us with proper training, promotions, places to rest, and proper provisions".*

It is the role of the management to ensure proper rest spots are available to pilots, particularly when they are working for long hours and subject to high operational demands. These factors have an adverse influence on pilot's reliability and escalate the level of operational stress, which has been confirmed across different industries as one of the leading factors in operational accidents. Accordingly, a general statement concludes the discussion with one about the working hours, which states that,

> *"Working in the day forces me to work under the sun for a long time. The sun light and the high temperature make me dizzy and unable to conduct further pilotage operations.*

> *Because of the frustration caused by the sun, I won't accept any constructive comments or suggestions and I try to conduct the operation as quickly as possible, which often leads to unsafe decisions".*

The above statement was agreed with by the majority of the pilots at this port, who want management to look at their operational needs in order to eliminate the effect of operational stress during pilotage services.

- ***Operational stress (OF-OS)***

Stress during operations has various forms. There exist, for instance, management stress, financial stress, commercial stress, and environmental stress. Management requires pilots to maintain high operational standards and practices to ensure the health and safety of their employees while operating and conducting port services. On the other hand, operators are required to observe their safety during their daily duties, which can be identified and managed by experience or training courses. In this port, pilots are subject to high stress, which is stated in the following summarised statement:

> *"We are subjected to high level of operational stress, and the management of the port has a central role in this stress. Management do not provide the required training, adversely affect operations, create conflicts amongst team members, and work without operational strategies and development".*

It is apparent from previous discussions that stress due to management practices exists in the form of a lack of adequate training and career progression. However, personal stress is also related to a number of factors, such as financial stress, family issues, health issues, and teamwork issues. Finally, stress caused by the behaviour of other operators can be due to conflicts with other operators, tug operational failures, and improper teamwork, which affect proper decision-making. Accordingly, pilots have stated that,

> *"Stress caused by other team members is important, since any failures made by other operators can adversely affect the performance, especially if that operator does not report that failure immediately".*

The majority of the pilots interviewed report that,

> *"It's common that the shipmaster misrepresents some non-existent equipment failure on board, which raise stress levels".*

The prevalence of operational stress can be identified since higher levels of stress can degrade or slow down the operator's ability to make proper decisions, adversely affect operator health, thereby preventing other team members from conducting operations safely. Maintaining the above factors will create a positive working environment that helps ensure safe marine pilotage operations.

- ***Working environment (OF-WEnv)***

To maintain high levels of organisational safety, it is essential that management maintain high operational standards by enhancing operational practices and encouraging a positive working atmosphere. The management of the organisation plays a vital role in ensuring a positive operational atmosphere by providing their employees with training, rewards, and listening to their needs. In addition, the pilot has a duty in conjunction with management and other team workers to ensure that effective working practices are in place. Some of the pilots have stated that,

> *"The management of our organisation has an impact on our daily working practices. We need training, promotions, better rewards, and nicer places to rest while we wait for further operations".*

Some other pilots have stated that,

> *"The adverse involvement of the management causes conflicts with other team members, which makes for an unpleasant working environment".*

Maintaining effective working practices helps maintaining high operator reliability on a daily operational basis. The management of any organisation must ensure a positive working environment in order to ensure high operational and safety standards.

3.7.2.3 Non-technical skills (NTS)

The knowledge base and technical proficiency of employees within high-risk industries are essential, and a large amount of a company's resources is spent on enhancing employees' technical proficiency. Around the mid 1980s, the aviation industry's focus was on the technological and technical aspects of aircraft and pilot training (Moorthy et al., 2005). This focus prompted research conducted by National Aeronautics and Space Administration (NASA), which found that human errors constituted around 70% of reported accidents, due to failures of interpersonal communication, decision-making, and leadership (Helmreich et al., 1999) which comprise non-technical skills. Moreover, operators' non-technical skills and component failures (situational awareness, decision-making, etc.) were revealed in accident analyses as culpable for adverse events in complex organisations, even when the operator has a high level of technical competencies (Sharma et al., 2011). Since the 1980s, researchers have tried to tackle the problem caused by NTS deficiency by developing a behavioural marker tool (Sharma et al., 2011; Flin et al., 2003; Yule et al., 2006; Yule et al., 2008; Sevdalis et al., 2008; and Healey et al., 2004). This tool is widely used in different industries and aims to structure the required training needs and evaluate those needs in aviation (Flin et al., 2003), maritime (Saeed et al., 2016) and health (Fletcher et al., 2004; Yule et al., 2012).

Operators' NTS are composed of a set of social and cognitive skills that demonstrate the operators' ability to perform their work. Variability in researchers' points of view in studying factors that adversely influence NTS was observed and is due to the varying nature of the industries where NTS are important. Proper enhancement of operators' NTS in high-risk industries is crucial in order to eliminate the consequences of human error (Helmreich et al., 1999). Due to the absence of investigation of NTS in marine pilotage operations, this research aims to highlight the negative consequences caused due to improper maintenance of NTS among pilots in a complex working environment. The aim of this research is to develop a comprehensive model for assessing the reliability of marine pilots by identifying the most dominant factors shaping operator reliability and the degree of interdependencies between those factors.

For that reason, an intensive literature review across different disciplines was conducted to open the discussion, identify operator concerns, and stipulate the main components of operator NTS relevant to the pilotage operation. In the interviews, pilots emphasised the significance of the following four NTS sub-criteria: Decision-Making skills (NTS-DM), Situational Awareness skills (NTS-SA), Communication and information sharing skills (NTS-CS) and Teamwork and Leadership skills (NTS-T&L).

- ***Decision-making (NTS-DM)***

Making proper decision requires the operator to maintain high levels of vigilance. Decision-making is not an easy process and is built upon numerous factors. The way that someone makes a decision varies depending on a number of conditions. Making a decision is a skill that can be built over time, not only within the organisation, but also in one's personal life. Accordingly, pilots must take into account other operational factors before making decision to ensure the safety of other operators. Some pilots argued that,

> *"Making decisions is a process only completed after developing a comprehensive operational picture that is developed based on different sources of information attained literally or explicitly from other team members involved in the pilotage operation".*

Making proper decisions requires decision-makers to gather the relevant information, establish communication links with different participants to share useful information, revise current operational circumstances, and implement new operational strategies. Accordingly, one pilot stated that:

“Proper decisions can only be made if all parties have properly expressed their thoughts”.

This statement initiated a discussion confirming what these thoughts referred to. The pilot discussed cases when shipmasters hid useful information that adversely affected pilots’ decisions. Shipmasters hide information because they do not wish to leave the port until they fix the problem or conduct specific pilotage operations, for which there is a higher financial cost. Moreover, direct contact with other team workers helps to re-shape and consolidate the pilot's decisions to meet the demands of any situation. For instance, the tug master has an important role in supporting the ship’s manoeuvre inside the port; whenever the tug master updates the pilot during the operation in terms of distance, the pilot can move on to making the next decision. However, sometimes the tug does not reply or does not tell the pilot when he starts applying the given order, which forces the pilot to ask him whether he has started working in order to develop a useful operational picture. In this case, the tug master increases the effort and stress placed on the pilot, and so it is useful to ensure the correct action in place. If the VTS operator informs the pilot that he is approaching danger or moving closer to another navigating ship, the pilot must reconsider his decision and reform his action.

However, the pilot's decision being agreed with by all the participants builds upon a comprehensive operational overview that is accumulated through different procedures with support from other parties involved in the same operation with similar operational objectives. This overview provides the pilot with awareness of the current operational situation and improves his decision-making.

- ***Situational awareness (NTS-SA)***

The pilot, during the pilotage operation, is required to monitor all activities and other team members involved in the operation. It is the obligation of the pilot and other workers to share all pilotage related information to make adequate decision. Situational awareness is a core skill that all decision-makers must maintain and observe closely to ensure proper orders, implementing procedure, and option generation. Accordingly, a number of pilots stated that,

> *"Observing all operational actions is a difficult process. We, as pilots, focus on the actions and response of the tug masters, ship engine, and ship movements to maintain and reassess current operational circumstances".*

It is difficult to comprehend all operational actions without having support from other parties. Pilotage operations are built upon the actions of teamwork and those with different operational responsibilities and procedures but the same operational goals. Accordingly, some pilots stated that,

> *"Situational awareness is a skill that is learnt through experience or courses that allow the pilot to understand the surrounding working processes shared by other team workers involved in the operation".*

Another pilot stated that,

> *"Situational awareness requires all parties to share the required information to all other team members and ensure operational safety and standards. It is highly dependent on the performance of other workers involved in the operation".*

Situational awareness is subject to the mental capacity of the operator and highly influenced by operator fatigue and body strength. It is key to maintain high operational awareness since proper decisions are subjected to the quality of situational awareness. This statement is confirmed by the majority of pilots, who have stated that,

> *"We can develop and maintain high operational awareness based on the performance and the quality of the information shared by other operators. The management also can adversely affect personal awareness since higher operational demand and stress could lead to fatigue, which adversely increases the probability of personal failures in maintaining operational awareness and leads to improper decisions being made".*

The significance of this personal skill can be seen in IMO, Resolution A.960 as amended, which recommends to all pilots that they have a bridge resource management course that explains the process through which the pilot can develop his/her situational awareness and other factors, such as decision-making and leadership, to maintain higher operational standards.

In this investigation, pilots considered situational awareness an essential process in decision-making. Thus, pilots have emphasised the significant role that situational awareness in their reliability and maintenance of higher operational performance. Moreover, since all parties involved in the operation work in different places, the only way that the operator can share the required information is via communication, which requires higher personal skill to adequately communicate with other parties.

- ***Communication skills (NTS-CS)***

Communication skills are a key ability that can critically affect the safety of the operation. Inadequate communication skills can reflect a lack of operational awareness, poor team working, and poor decision-making.

Many interviewed pilots stated that,

> *"Communicating all significant operational information clearly and cohesively is a skill that cannot be managed by all parties. It plays a critical role in our decisions, since missing data and reporting unclear information leads to developing a situational picture that does not reflect reality".*

This skill can affect the nature of the team and leadership style for which an operator is characterised. This skill is built upon the ability of the operator to manage external factors that require operator reliability, such as management and operator complacency. Accordingly, many participants stated that,

> *"As previously said, stress that occurs due to management working practices are found to adversely affect operator communication style and clarity. Pilots tend not to communicate all relevant information".*

Moreover, pilots have emphasised the importance of other operators involved in operations and stated that,

> *"The involvement of other team members can adversely impact pilots' personal reliability. This includes the ability to make decisions, build proper teamwork, and communicate adequately".*

To summarise, all pilots seem to agree that the main purpose of communication is to regulate, control, motivate, express feelings, and convey information with other team members. Improper use or lack of transparency in the communication channel between members are the principal causes of most conflicts that occur during operations.

- ***Teamwork and leadership (NTS-T&L)***

An operator's ability to maintain adequate non-technical skills can be built upon teamwork and leadership skills. Working as a team in a complex working environment is considered challenging, since it requires each party to understand the operational process and the nature of each party's role. Conflicts between parties is one of the main influential factors that degrades operator reliability. However, managing conflicts between parties requires managerial skills that can be formed through an operator's leadership and teamwork style.

The majority of pilots stated that,

> *"Teamwork is an essential component and the heart of our operation, since we find it difficult to manage all parties with so many different operational roles and perspectives. It requires a lot of personality to manage other team members in an effective, friendly way".*

Leadership style and personality are developed in highly qualified operators. Managers and leaders must possess a specific skill-set. Effective and skilful leaders are supportive and open to criticism from other workers and can successfully manage groups of any size Moreover, the leader should always be the key player in a team, motivate other team workers based on their operational limitations, and be open towards diverse cultures.

Accordingly, most pilots interviewed pointed to the significance of leadership in managing efficient teamwork to maintain higher operator reliability in the form of non-technical skills. One pilot stated that,

> *"Skilful leadership has the ability to manage operational conflictions that arise due to managerial or personal conflicts. Leaders can cope with operational stress, degradation of team member reliability, and critical situations professionally. A team depends on its leader, so proper communication should be established in order to share operational knowledge and make proper decisions"*

It is apparent that effective teamwork is a skill subject to personal leadership styles. Moreover, effective teamwork leads to collaborative operational alliance in the form of operational sharing goals and information that helps decision-makers receive the required information through adequate communication processes and make decisions that best benefit all members of the team.

3.7.2.4 Fitness and strength (F&S)

Operator fitness and strength are crucial in many high-risk industries and have a significant role to play in successful operations. However, fatigue caused by a variety of factors has been found to have a significant impact on operator fitness and strength (Riahi et al., 2012). This relationship is prevalent in all fields that require high levels of physical and mental performance, which is the case in pilotage operations. Pilotage requires the pilot and other operators involved to maintain high levels of physical and mental strength throughout all stages of an operation. Stress at work cannot be fully eliminated, though the organisation's management and the operators can manage stress through a variety of approaches.

The links between human fatigue and operator fitness and strength have been identified across different industries (Riahi et al., 2013). Moreover, fatigue has an influence on the operator NTS, which means that fitness and strength are associated with operator NTS and TP. Consequently, it is important for the port authority, when assigning a pilot to handle a ship, to ensure that the pilot is physically and mentally prepared. Moreover, the International Maritime Organisation (IMO) resolution A.960 (2004) and the American Bureau of Shipping (ABS) Guidance (2003) have stated that, "The fundamental purpose of the pilot fitness assessment is to ensure that the individual pilot is fit to handle the ships calling at that port".

Based on interview responses, three criteria were identified that constitute operator fitness and strength. These factors are considered by the operators to be essential to their performance. In addition, pilots have highlighted the current organisational factors that influence their fitness and strength, namely operator age, personal health, and physical and mental strength.

- ***Operator age (F&S-OA)***

Pilots have stated that operator age is essential to pilots, as their job is physically demanding and requires them to be physically fit at all times. It is recognised that the pilots gain valuable experience with time, though getting older potentially weakens their body strength. Accordingly, some pilots have stated that,

> *"Getting older might not change a pilot's ability to conduct safe operations, as it is not necessarily true that the pilot gets weaker. In our case, management does not provide us with proper medical care as many other companies do. It is difficult to get treatment in the hospitals here as the majority of them aren't free".*

Some other pilots added that,

> *"Since management does not provide us with proper provisions, such as well-ventilated resting areas and complementary fitness plans, it is hard for the operators to keep fit when getting older".*

Operator age is essential since a number of variables of operational performance depend on this factor. It can be observed across the participants that older pilots have a wider range of skills than younger pilots because of their extensive experience. Older pilots have further operational understanding than junior pilots. However, these pilots are also subject to stress and must be able to deal with the same issues with which they have dealt for their entire lives. The number of working hours, operational demands, and working environment, as highlighted in Section 3.7.2.2, were linked negatively with operator age, as stated by one pilot:

> *"Working demand increases operational stress, which affects our ability to conduct a number of operations. The working environment on top of that has an even greater adverse effect".*

This statement has been agreed with by most of the seniors of age 40 and above. Some senior pilots stated that,

> *"Operator age can be advantageous to operations, since older pilot have more experience and are better at analysing different situations and managing different cases, especially if they maintain their health by avoiding detrimental habits like smoking and drinking".*

Another pilot stated that,

> *"The majority of older pilots have the ability to analyse operations sensibly as their operational awareness is considered, in most cases, better than the younger pilots".*

Another pilot stated that,

> *"It is not necessarily true that we get weaker as we get older, it depends on many circumstances. However, management can help us to monitor this issue by providing us with medical care and monitoring personal activities with complementary fitness programmes".*

Accordingly, most pilots are judged on their ability to conduct a variety of operations. All pilots agree that getting older means being more prone to disease, irritated by the opinions of others, and becoming weaker in terms of physical strength. However, getting older also means being highly ranked, conducting many ships' operations, and having a wealth of experience.

- ***Personal health (F&S-PH)***

One of the main concerns raised by pilots is health. The majority of pilots agreed that health is essential in maintaining higher operational reliability. Since pilotage operations require considerable concentration, physical exertion, and proper decision-making, health is a priority for pilots. Health can be ensured by managing operational stress, maintaining proper management style, providing operators with proper provisions and places to rest, and the pilots looking after their own health. Accordingly, a number of pilots stated that,

> *"We as pilots are subjected to higher operational stress provoked by the nature of the operation and the management practices".*

Other pilots stated that,

> *"Management introduced new rules and operational standards without allowing us as pilots to learn the objectives and goals behind the new rules. This implementation increased our operational stress, since they punish us if we don't follow regulation".*

Stress as a result of interactions between other operators involved in the pilotage service is considered influential in pilot health. Since inappropriate behaviour and inadequate operational information can result in higher operational stress, there is a greater chance that the pilot suffers from nervousness and health problems. Stress was prevalent at all stages of the operation and fluctuated based on the ship position, ship condition, and the status of the workers involved in the operation.

- ***Physical and mental strength (F&S-Ph&MS)***

The majority of operators suffered from decreases in body strength. Older pilots are highly subject to illness and loss of strength. Pilotage service, due to the physical demand, requires higher body strength. The pilot at this port stated that,

> *"We are regularly checked medically by an authorised medical centre, to ensure our ability to conduct operations. It's just a routine procedure".*

Another employee stated that,

> *"Although we undergo medical checks on a regular basis, management does not provide us with a proper working environment, as mentioned before".*

Although medical checks can confirm some health issues, some major diseases or illnesses leave pilots unfit to conduct operations, and management should not allow the pilot to continue with further operations. Pilots at this port have confirmed the significance of body strength in conducting pilotage services. Moreover, the pilots confirm that management do follow their medical policy, as pilots can continue conducting pilotage services upon passing the routine medical test to confirm their ability to safely conduct operations.

Accordingly, an updated hierarchy structure for the main operators involved in a marine pilotage operation including criteria of an MP’s and sub-criteria development that designed based on the interview discussions were shown in Figure 3.4.

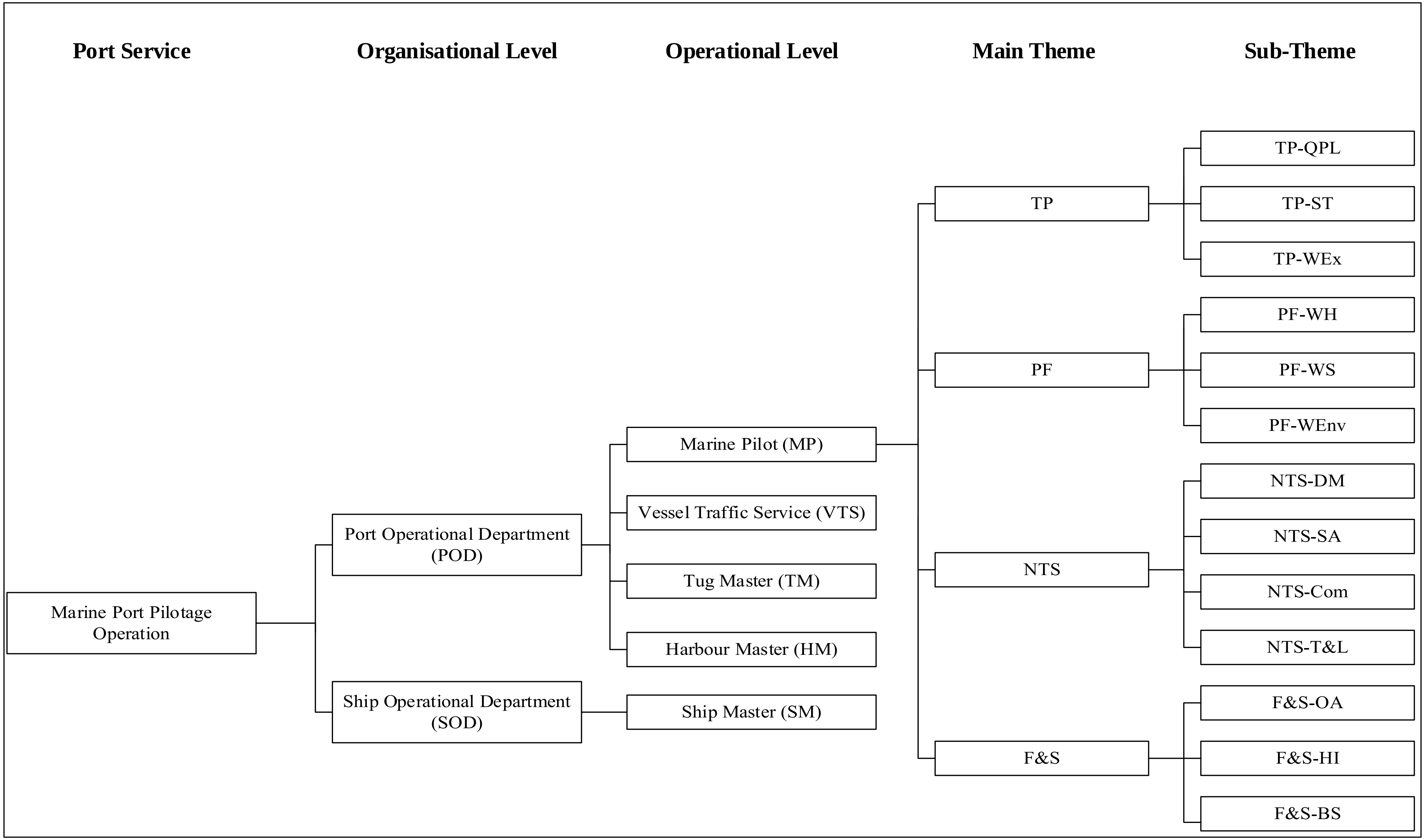

Figure 3.4. Marine Pilot’s Reliability criteria and sub-criteria

3.7.3 Port accident analysis

This section analyses four accidents that occurred during port pilotage operation. Three of these accidents, two groundings and one collision with the jetty, occurred over the last five years. The fourth accident occurred while the researcher was conducting this investigation, and two big ships were close to collision in the middle of the port in a near-miss situation. The researcher investigated all parties involved in the operation and has commented on the current organisational working practices within this port. The details of this port are not revealed for economical, personal security, and privacy reasons.

3.7.3.1 Case one (grounded ship)

A ship ran aground during night shift when preparing to leave the port after completing her cargo operation. Different parties, namely the shipmaster, pilot, VTS operator, and harbour master, shared the fault.

According to the regulations that manage the safe navigation of ships, the shipmaster was largely responsible for this incident for the following reasons:

1- He did not apply the rule of the road standards stipulated by the international maritime organisation in accordance with collision avoidance regulations.

2- He did not challenge the pilot’s decision to leave the ship before arriving at the pilot station located after the outer gate navigational buoys.

3- He misunderstood the instructions given by the pilot to pass the inner gate navigational buoys, which reflects improper communication that caused improper decision-making.

4- He was fatigued after prolonged working hours filling in paperwork, supervising cargo operations, and preparing for the next voyage.

The pilot's faults were as follows:

1- He conducted the operation and left the ship even before entering the channel through the inner gate navigational buoys. Leaving the ship before the pilot station is not allowed for any reason, and port policy stipulates punishment that can void this pilot's licence and mean a significant wage reduction for several months.

2- The pilot left the ship as he wanted to meet his friends for a dinner.

The VTS operator's faults were as follows:

1- It is his responsibility to monitor the movements of ships using any means of navigational equipment to provide advice to the pilot and shipmaster. This communication was not applied at the time of the incident.

The harbour master's faults were as follows:

1- He did not ensure that the operation was conducted in accordance with port policy.

2- He was not monitoring the operation closely nor listening to the pilot's orders.

Because of the actions of the above mentioned parties the ship ran aground (see Figure 3.5). The ship experienced minor damage as it was not at full speed and had just cast off from the jetty. Consequently, in accordance with port policy, all parties were punished. The ship agent has paid a fine, while the other parties faced wage penalties.

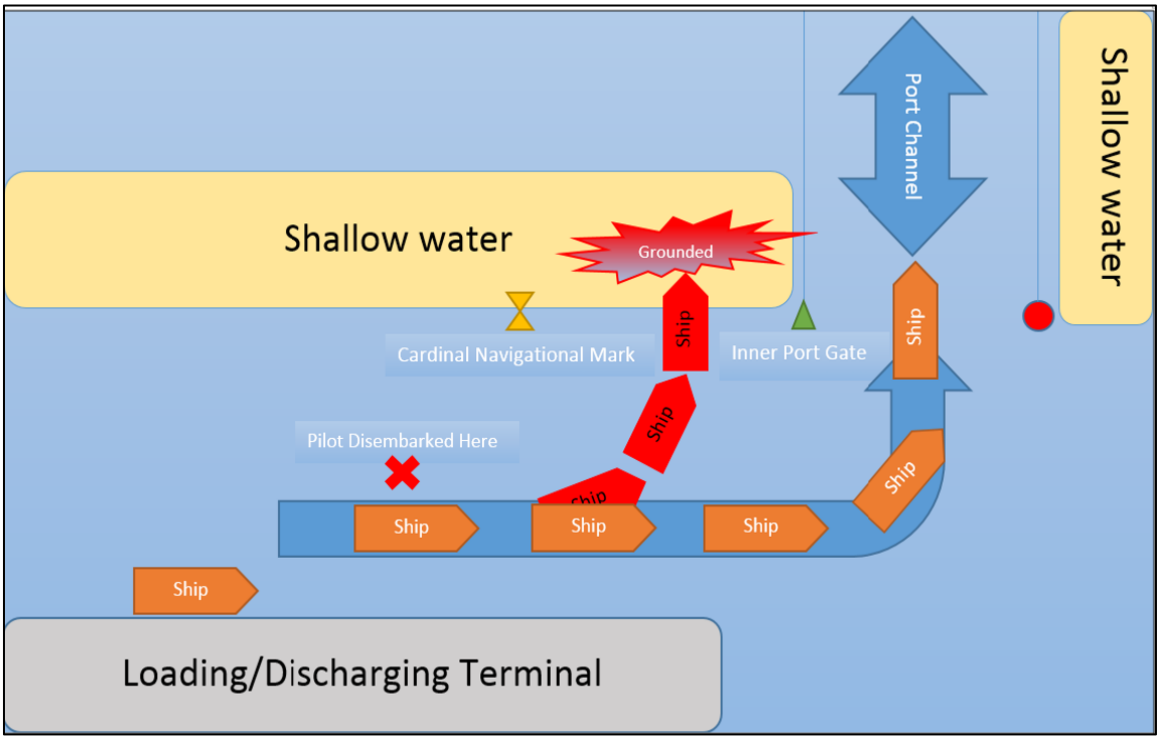

Figure 3.5. Grounded ship footage (case number one)

3.7.3.2 Case two (grounded ship)

A ship ran aground during the night shift while approaching the jetty from the pilot station, at which point the pilot was on board. Going from the pilot station to the jetty in normal conditions takes around 35 minutes. When the ship was approaching the jetty, it ran aground in shallow water. The grounding was largely due to the shipmaster relying on the pilot to conduct the operation without ever challenging his actions. Moreover, the shipmaster did not monitor the ship’s position as required nor comply with the COLREG rules. The pilot in control of the ship was a senior pilot and working on his second consecutive night shift. The pilot fell asleep at the time, and so the ship was not controlled by any official, of which the bridge team was not aware. In addition, the VTS operator was not monitoring the ship as it approached the shallow water and was therefore unable to warn the pilot and shipmaster of the proximate hazards. The harbour master also never warned the pilot and the shipmaster of the circumstance. The ship ran aground without causing pollution, loss of life, and navigational hazard.

3.7.3.3 Case three (ship collided with jetty)

The pilot conducted the berthing operation with the support of two powerful tugs. The pilot was a senior pilot and experienced in conducting pilotage operations for several years with a variety of ship types. The main catalyst of this incident was that the pilot had spent a lot of time on side talks and jokes with other pilots and tug masters while closely approaching the jetty. The pilot not fully aware of the operation as the side ship speed increased rapidly. The channels used to communicate between parties were full at the time, so the communication was interrupted, and a collision occurred.

The different parties involved were the shipmaster, the pilot, the tug, the VTS operator, and the harbour master. In accordance with port policy, it is not permissible to communicate with the equipment used during operations at any time. Communication between parties must be relevant to the operation at hand. All communication during operation should be in the port's official language, English.

The shipmaster did not challenge nor pay attention to any of the ship safety concerns. The pilot lost control of the situation because of improper or delayed actions. The tug master was dismissed, as he was unreasonably unable to assist properly. The VTS and harbour master did not force operational standards in terms of preventing irrelevant communication to concentrate on the operation. As a result, the jetty was severely damaged along with the ship's hull. This incident cost the shipping company millions of dollars in order to repair damage caused to the jetty.

3.7.3.4 Case four (near-miss)

This incident occurred during an investigation that was taking place at this port. The researcher has experience as a seafarer on international ships and as a former tug master. An incident between the two ships, a bulk carrier and a large container ship, was observed in which both ships met together at the middle of the port docks, as shown in Figure 3.6.

The bulk carrier was approaching the designated jetty, and the container ship had completed its cargo operation and was heading towards its next port of call. According to port regulations, it is not permissible for any pilot to conduct simultaneous ship handling operations, i.e. to have one ship departing as another ship is approaching, or to pass side-to-side inside the navigational channel or docks. Therefore, the pilot handling this operation breached the port's regulations.

The investigation involved different parties in this operation. First, the tug masters involved in the operation were approached and questioned. The tug masters who were on standby and assisting the approaching ship were suddenly called by the container pilot to clear the path. This call shocked the tug masters. After the incident, the tug masters filed a complaint, as they had already been in position and then been required to change their plans, which reportedly caused them significant stress. The VTS operator was also approached to discuss the incident.

Surprisingly, the VTS operator was not aware of the incident and stated that,

> *"I noticed that the departed containership met the bulk carrier in the middle of the dock, where the container pilot cast off ship lines without permission, while the approaching bulk carrier was in the middle of the channel and had permission to proceed towards the designated jetty with the pilot. The container pilot announced, which attracted my attention, that he left the jetty without using tugs when reaching the middle of the front port's dock".*

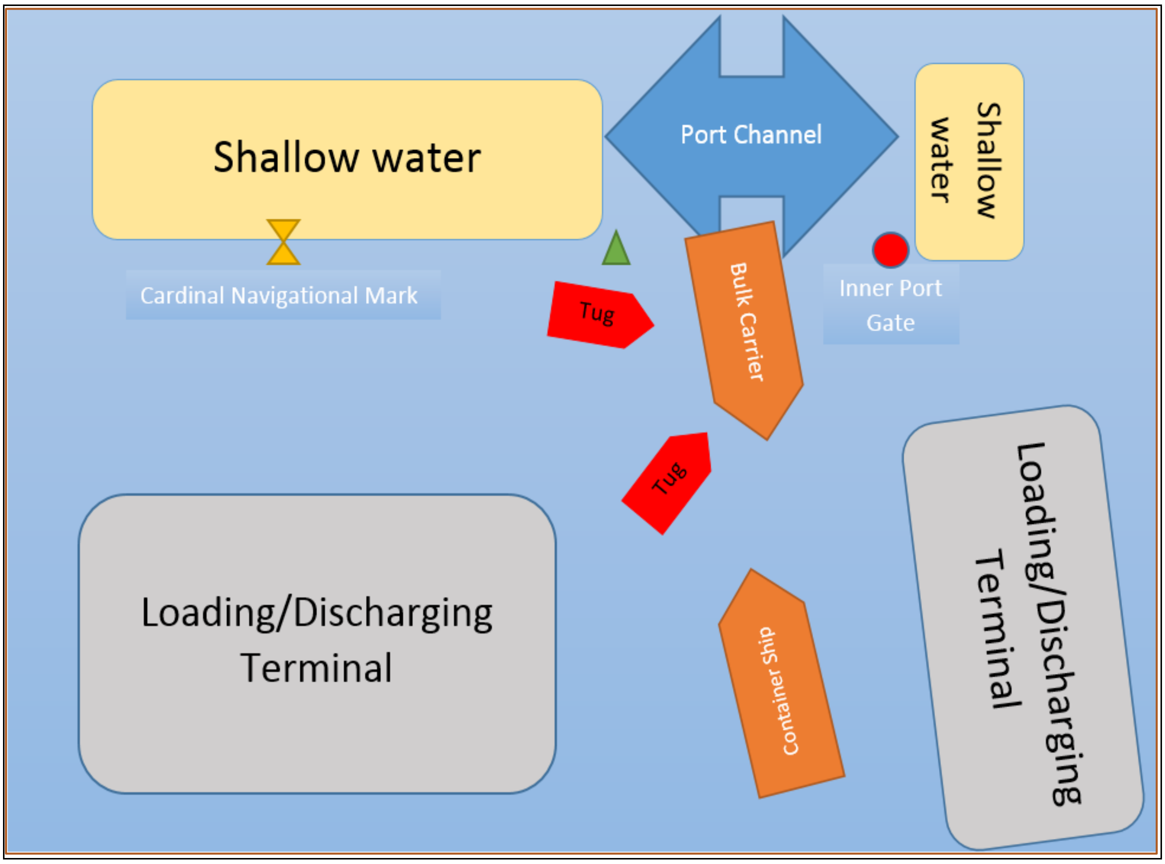

Figure 3.6. Near-miss incident (case four)

No pilot is allowed to proceed with any action without permission from the VTS operator, who in turn takes orders from the HM. The pilot on board the bulk ship was then approached to discuss the case. The pilot commented on the incident and stated that he was unaware of the leaving ship until reaching the middle of the channel, at which point there was no chance to stop and return. He stated that,

> *"The captain was frustrated when he noticed that the ship was leaving and would meet another ship so closely in the dock".*

The same pilot commented that,

> *"Although the pilot on board the container ship has a very long experience and is one of our most highly valued experts, it is not okay to breach port policy".*

Lastly, the HM was asked if he had noticed any near misses during the last few days, to which the harbour master replied that nothing had happened. The harbour master was then asked again about the last few days, but he still insisted that he had no memory of the occurrence.

Accordingly, this case has been organised into the following stages:

1- The shipmaster of the container carrier did not challenge the actions of the pilot when another ship was approaching them in a single navigational channel.

2- The pilot, despite being experienced, did not obey the port's policy stipulated to maintain higher operational safety standards.

3- Other team members, such as the pilots and tug masters, did not complain to management because of loyalty amongst colleagues.

4- The harbour master was completely unaware of the situation, although he should monitor all navigational movement as his first priority. Furthermore, it is the VTS duty to inform the HM immediately of MP misconduct.

5- It is apparent that shipmasters did not contradict the action of the pilot because of fatigue and being focused on other tasks, such as paperwork, cargo plans, and emailing the company. As such, shipmasters were unable to conduct navigational processes to aid the pilot.

6- The teamwork at this port was affected by poor management practices that affected those conducting the pilotage operation.

In summary, to analyse the findings from the above investigation, the four accidents, and the findings from the field interviews and observations, the Delphi technique and AHP are used and results are presented in Chapter 4.

3.8 Conclusion

This chapter highlighted current marine pilotage operational practices at a marine port. The methodology used in this chapter identified factors that influence marine pilot reliability during port pilotage operations. Most of the identified factors highlighted in the literature were confirmed as essential during field investigation. However, some factors mentioned fall outside the scope of this study and require further investigation. The identified factors were combined for quantitative analysis, as highlighted in Section 4.4.1 (see Table 4.3), in order to build an effective MPRI. For the research triangulation and to ensure research validity and reliability, the study used various data collection methods. First, the researcher conducted a field observation of marine port pilotage operations to identify key operators and the degree of interaction between them. Secondly, semi-structured interviews were conducted using focus groups to gain an accurate understanding of the entire operation. The experts involved in the discussions expressed their perspectives on the topic, including factors that contributed to their performance. This stage confirmed that most of the identified factors used in different disciplines are essential in developing an effective MPRI for the study. The novelty of this step is on developing a holistic model consisting of the identified factors from different disciplines as one set. Moreover, the degree of interactions among factors are pointed out through the discussions. Third, a comparative investigation was conducted by investigating accidents under pilotage operations at a port to comprehend existing operational practices.

Chapter Four: Quantitative Analysis of the Weights for the Marine Pilot's Reliability Index (MPRI) using a Delphi Technique (DT) and Analytical Hierarchy Process (AHP)

4.1 Chapter Summary

The previous chapter identified key factors that critically shape a marine pilot's reliability index. Four main criteria, along with 13 sub-criteria, were identified qualitatively. Since this work proposes a mixed-method approach, this chapter will cover the quantitative part, which complements the qualitative part from chapter three, to test the validity, reliability, and trustworthiness of criteria identified qualitatively based on experts' opinions; the researcher has proposed the Delphi technique to achieve this aim. The Delphi technique (DT) has been used widely across different disciplines to test the validity and degree of acceptance among experts on identified criteria. This step will validate the structured model for the next step in achieving this research topic's objectives. Following the model validation process, the researcher will use analytical hierarchy process (AHP) to assign weights to the identified factors, which represent the degree of importance based on experts' opinions toward each criterion and sub-criterion regarding shaping a marine pilot's reliability index. The weight identified from this chapter will complement the next chapter's method as appropriate. The framework of the proposed methods for this chapter are presented in Figure 4.1.

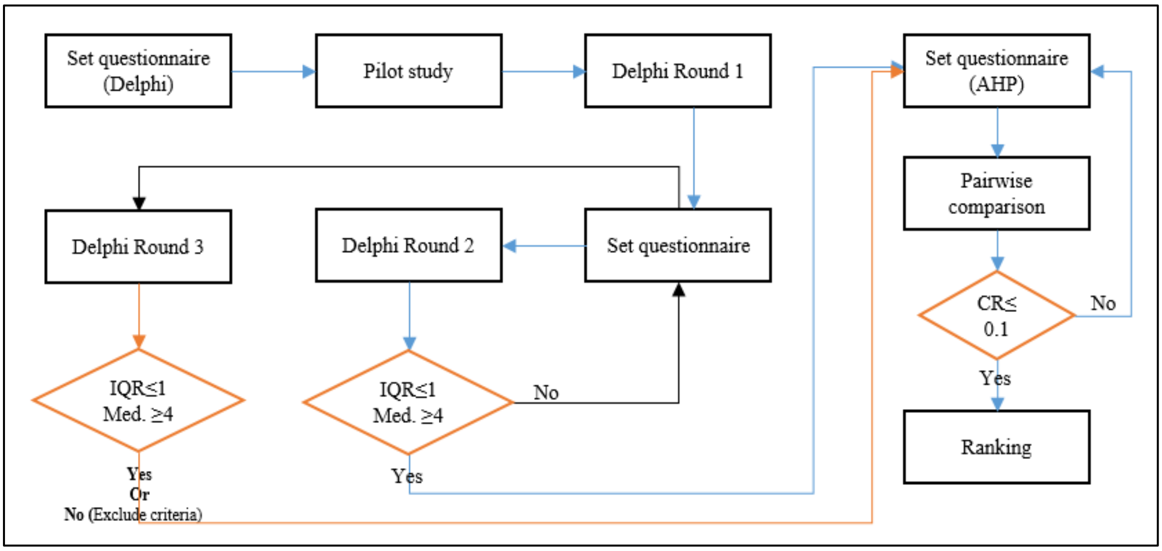

Figure 4.1. Proposed methods framework

4.2 Introduction

The dynamic and transient features of maritime industry make investigating a marine port pilotage operation highly challenging. Scholars tend to use non-traditional research methods such as surveys, interviews, and group brainstorming to achieve research objectives, but those methods involve confounding factors and accessing sensitive information (Hallowell and Gambatese, 2009). This study aims to develop a reliability index for a marine pilot within port pilotage operations using a set of criteria identified qualitatively based on the experts' opinions presented in chapter three, along with support from academic literature in different fields. Given the lack of certain and clear criteria for developing a pilot reliability index that helps assess an operator's reliability during the operation, it was first necessary to examine the incorporated criteria identified through chapter three's qualitative process and collect feedback and reach consensus among these criteria using an effective iterative group communication process. This was to be done by using different assessment tools that define criteria and then selecting the most appropriate factors for developing the index. This qualitative tool can provide a comprehensive view into social interactions within organisational process, but the challenge is how to meet the organisational needs through developing a novel tool.

The majority of studies require engaging the experts' opinions on the first stage, which is called a participatory research method. The aim of participatory research is to obtain a methodological assessment tool that engages experts in the research efficiently, adopting a proper communication method throughout the research process to achieve a useful result that can be applied in reality (Morris, 2017). This tool's characteristics will provide the experts with opportunities to share knowledge and operational ideas with each other. During the discussion that was conducted in the focus-group interviews presented in chapter three, the experts expressed their feelings towards the operation in different ways.

Some agreed with the statement while others objected or said nothing. This variance could affect the results and the analysis that the researcher follows in developing the general criterion as the researcher has used different expressions to present these variances such as ‘the majority’ ‘most of the participants’ and ‘this statement was agreed by’. To avoid bias with this type of information, the researcher used a technique called the Delphi method to reach a consensus among experts regarding the identified criteria. Moreover, this step will confirm the validity and trustworthiness of the identified factors that built upon the qualitative research.

4.3 Research backgrounds

The techniques proposed to achieve the desired outcomes in this chapter are the DT and the AHP. The DT was used to elicit a consensus among experts in terms of the identified criteria highlighted in the literature, which was later confirmed through field investigation in Chapter 3. The AHP was used to assign a relative weight to each identified factor and rank them accordingly. Therefore, the following sub-sections provide an overview of the proposed methods used in this chapter.

4.3.1 Delphi method

The Delphi method is a participatory technique that deals with experts’ opinions by collecting their views on studies that lack a conceptual framework. It has a structural process that builds upon a number of sequential questionnaires sent out in rounds and then subjected to controlled feedback (Keeney et al., 2001); this acquires a consensus opinions among a group of experts on that particular study (Linstone and Turoff, 1975; Powell, 2003; Kennedy, 2004). Delphi was invented by RAND Corporation in the 1950s by Dalkey and Helmer (1963) as an effective means for collecting and soliciting expert judgments. Its main objective is addressing an incomplete state of knowledge or lack of agreement on an issue that must achieve consensus among a group of experts (Powell, 2003).

This method has been used for decades to investigate the scientific use of expert opinions strictly on matters of defence and military strategy (Keeney et. al., 2001; Landeta, 2006; Morris, 2017). For sensitive reasons, it remained privately in use within that period (Dalkey et al., 1969) before it was used in public research for the first time by Helmer and Quade (1963), to investigate the development and planning of economies. Since then, Delphi became widely popular across a broad spectrum of subjects (Asghari et al., 2017; Aengenheyster et al., 2017; Ab Latif et al., 2016; Stebler et al., 2015; Landeta, 2006; Powell, 2003; Graham et al., 2003; Hasson et al., 2000; Gibson, 1998; Beech, 1997; Butterworth and Bishop, 1995).

One of the main objectives of the Delphi technique is to gather and clarify information on a related topic by synthesising experts' judgements to develop a conceptual framework and obtain the most reliable consensus (Dalkey and Helmer, 1963; Okoli and Pawlowski, 2004; Gordon and Pease, 2006; Landeta, 2006). Moreover, since this method is widely used for quantifying uncertain variables and reaching a statistical consensus, it can be used to help clarify or develop conceptual frameworks. Delphi has proven its applicability and is widely used to support policy-makers' decisions and predictions (Pill, 1971; Gordon and Pease, 2006; Landeta, 2006). Moreover, it is capable of structuring and organising effective communication among a group of people (Powell, 2003), which helps obtain information that lacks theoretical forms or has not been conceptualised systematically, and solving a complex problem (Linstone and Turoff, 1975). Therefore, most of Delphi studies gather experts' opinions in a field that has non-solid and dynamic notions in a sequential process (Morris, 2017).

4.3.1.1 The Delphi process

Although there is no standardised process for conducting Delphi research, many studies indicate its varying degrees of interpretation and flexibility (Green et al., 1999; Powell, 2003). However, the main principle that characterises the method remains consistent, as it provides an accurate consensus on information (Rowe et al., 1991; Jones and Hunter, 1995) via repetitive sets of sequential questionnaire rounds.

The sequential approach that Delphi utilises via conducting a set of multiple questionnaire rounds aims to gather a consensus on information among a group of experts (Green et al., 1999; Keeney et al., 2001). Utilising a questionnaire has an advantage as it gathers a large set of information across a large number of experts in different geographical locations (Keeney et al., 2001). Accordingly, this method is repetitive, as experts involved in the study must be consulted at least twice on the same set of questions. The main objective of this process is to let the experts reconsider their answers when compared to other experts' opinions. It maintains a higher level of participant anonymity with their answers, as participants cannot recognise each other. The advantage of anonymity is that it encourages true opinions by eliminating the negative pressures to appease other experts. Another feature of the Delphi method is controlled feedback, in which a group coordinator exchanges information between the expert panels and dismisses all unrelated information. This process helps form questions that can assess experts' responses statistically and quantitatively (Landeta, 2006). Therefore, the process of Delphi is composed of four features: anonymity, iteration with controlled feedback, statistical group response, and expert input (Goodman, 1987; Landeta, 2006). The following section will discuss these features' application in this study.

4.3.1.2 The expert panel and sample size

According to Powell (2003), studies using the Delphi method cannot succeed without an expert panel. The Delphi method is built on the expertise of the panel members (Green, et al., 1999), because the method does not use a random population sample when carrying out research (Goodman, 1987; Keeney et al. 2001); rather, it employs expert respondents on the particular research topic. Therefore, according to McKenna (1994), the expert panellists are a group of ‘informed individuals’ and field specialists. The Delphi method can thereby reflect and test the concerned investigation more precisely because the study is run by these expert panellists. This practice assures content validity, as the representative experts have working knowledge, while non-experts will not yield better results. Therefore, the ‘expert panel’ must consist of experts with related working knowledge on the specific subject being studied (Green et al., 1997; Green et al., 1999).

The panel of experts must have a number of experts involved actively throughout the process stages. The variation on Delphi process reflects variation on how many incorporated experts are needed. The number of panellists suggested by Reid (1988) ranges from 10 to 1,685, while others estimate a number according to the scope of the study and available sources (i.e., time and money) (Hasson et al., 2000; Powell, 2003). Some point out that the reliability of answers increases steadily if the number of participant judges increases. However, there is a lack of empirical evidence showing that the number of participants can affect the reliability and validity of expert opinions (Murphy et al., 1998). Moreover, the Delphi process does not target the number of experts participating for statistical purposes, but rather looks to experts’ qualities for more valuable outputs (Powell, 2003). To achieve this, it is important to ensure the ability and willingness of participants to express their valid contributions, and they must have sufficient knowledge and perceptions on the subject.

4.3.1.3 Participant anonymity

The advantage of anonymity, as aforementioned, is that it encourages honest opinions not pressured by other participants' personalities and statuses. Expert opinions lose accountability if there is lack of anonymity (Goodman, 1987). The advantage of being anonymous is that it enables the expert to express unbiased opinions in regards to the concerned study (Couper, 1984). This supports the analysis carried out in chapter three in identifying significant criteria that constitute operators' characteristics during a marine pilotage operation. Moreover, it helps overcome any possible biases by encouraging respondents to be honest and open in their opinions on certain issues. This provides useful data sets to any researcher using this method for further investigation on that subject. Moreover, each expert's opinion is given the same weight and importance in the analysis, as the responses to given questions are independently answered (Keeney et al., 2001). Therefore, bias is eliminated because respondents are not identified to each other (Jeffery, 1995).

Researchers, such as Goodman (1987), highlight that complete anonymity may encourage 'ill-considered judgement' if the expressed views lose accountability. Other researchers, such as Keeney et al (2001), state that complete anonymity when using this method cannot be guaranteed for two reasons; first, the researcher knows the participants and their answers; second, in some studies, panel members know each other, but their answers remain anonymous, as their answers cannot be attributed to the speaker. Maintaining higher level of participant anonymity may prompt other members to participate especially if they know they have a shared interest in participating in that study. Therefore, McKenna's (1994) term 'quasi-anonymity' means that the panellists may identify one another, but individual judgements remain strictly confidential when conducting Delphi rounds and analysis.

4.3.1.4 Delphi questionnaire rounds and data analysis

Delphi is a systematic process employing a number of structured questionnaires that aim to elicit agreement among experts on a certain subject of interest. Prior to the process, the subject of interest is marked by a lack of consensus regarding multiple criteria as highlighted through the interview process, and that lack of consensus may significantly impact the process of a study. Typically, this method involves a number of rounds comprised of panellists who elicit data, followed by a data analysis to refine expert opinions in a repetitive process (Green et al., 1999). The number of questionnaire rounds varies from at least two rounds and is subject to consensus among panellists (Beretta, 1996). On each round, the panellists are encouraged to freely express their opinions and suggest, reject, and reconsider their judgement from previous rounds on any given criteria, which in turn indicates the degree of consensus. Therefore, the greatest difficulties are posed in the first round (Green et al., 1999).

The first round starts with an open-ended questionnaire, which allows the panellists to express their opinions freely (Powell, 2003). This process might generate a large number of factors, especially if the researcher uses an inclusive approach (Procter and Hunt, 1994; Keeney et al., 2001), and could discourage panellists from participating in the subsequent rounds. As the main scope of the first round’s questionnaire is to generate ideas and ask panellists to respond and comment on identified issues, researchers tend to provide pre-existing information for ranking or response (Keeney et al., 2001). This approach might bias the responses or limit the available options. However, the pre-existing information could efficiently tackle the amount of time consumed getting responses (Duffield, 1993; Jenkins and Smith, 1994).

After obtaining first round results, any subsequent rounds are structured questionnaires incorporating feedback from round one. According to Walker and Selfe (1996), the analysed data obtained by each round must be circulated back to panel members, as the data can encourage panel members to stay involved in the study. This process efficiently collects experts' opinions and subjects them to controlled feedback (Buck et al., 1993). The feedback given to panellists is vital, as it is the only mode of communication among experts (Murphy et al., 1998). In addition, returning feedback to participants is a unique and interesting practice for all concerned (McKenna et al., 1994). Therefore, the development of the organisation and its staff's needs can be linked by engaging experts in the study, as the experts present their concerns collectively.

One of the main concerns when applying the Delphi method is the decline in the rate of response as the study progresses (Keeney et al., 2001). According to Buck et al (1993), achieving a consensus among panellists requires involving participants in the research until the end of the process. The declining rate of response issue is one of the main criticisms of this method, and it mostly happens during the final round. This can explain why most researchers limit their study to two or three rounds rather the traditional Delphi method of four rounds (Keeney et al., 2001). Moreover, researchers are encouraged to balance factors that significantly influence willingness to participate, such as time, cost, and fatigue (Rowe et al., 1991; Powell, 2003).

4.3.1.5 Reliability and validity issue

Some researchers criticise the Delphi as having no evidence of information reliability (Williams and Webb, 1994; Walker and Selfe, 1996). This was justified by Walker and Selfe (1996) as if similar information were given to a number of panel members when using the Delphi method, the same result could not be guaranteed. However, other researchers have found the technique to have reliable results and effectively report the same results after 16 years in the same field of study (Ono and Wedemeyer, 1994). In addition, the technique has been criticised for its content validity. As Goodman (1987) asserts, the researcher cannot influence the survey development stage, which could have implications on its content validity. Contrastingly, if the participants have knowledge in the area of the study to represent the panellists, content validity can be expected (Goodman, 1987). Thus, using criteria such as transferability, credibility, and applicability of results might be more appropriate than relying on psychometric criteria (Keeney et al., 2001). Jairath and Weinstein (1993) have repeatedly reported the importance of conducting a pilot study to not only identify wording difficulties but also enhance the feasibility of the administered questionnaire. Few researchers conduct a pilot survey before the questionnaire round. As a result, the pilot survey must take place before every questionnaire round or be limited to the first implemented survey (Keeney et al., 2001).

4.3.2 Analytical Hierarchy Process (AHP)

The AHP technique is considered one of the most powerful and widely used methods to express fuzzy information, which conventional techniques, such as fault tree analysis (FTA) and failure mode effect and criticality analysis (FMECA), are unable to account in discussing the uncertainty that results from system operations (Al Yami et al., 2017). Fuzzy information cannot be expressed formally using crisp variables. However, using fuzzy forms of assessment enables a gradual transition between assessment states to overcome uncertain expressions (Wang, 2003). Accordingly, many advanced multi-criteria decision-making (MCDM) techniques have been incorporated using fuzzy theory such as fuzzy hierarchical aggregation method and conjunction implication methods (Sun, 2010; Al Yami et al., 2017). The AHP is regarded as a suitable technique when making a choice between complex criteria derived from a rational scale known as a membership function and was first developed by Saaty (1965). AHP is based on the subdivision of a problem in a hierarchical structure and aids in organising the rational analysis of the problem by dividing it into smaller constituent parts. Therefore, the main objective of the AHP is to derive the degree of importance, in terms of weight, for a set of operational activities (Saaty and Vergas, 2012). The AHP method is a comprehensive framework used to manage rational and irrational data, when dealing with multi-objective, multi-criterion, and multi-actor decisions, with and without certainty for any number of criteria and/or alternatives (Al Yami et al., 2017). This is a multi-criteria decision-making (MCDM) approach that can be used for solving complex decision problems built in hierarchical forms that contain multiple levels, namely objectives, criteria, and alternatives. Moreover, this method can also give a preference list of the considered alternative solutions in the form of a hierarchy structured model (Bentivegna et al., 1994), as it can be used to analyse different types of research using both qualitative and quantitative variables (Chang and Chen, 2011). Such a hierarchal structure helps the analyst provide decision makers conducting a multi pairwise comparison, with a tool to observe the influence of an element that significantly affects the operation in a hierarchical model. Moreover, it can also allocate a resource among different activities by highlighting the most significant activity through ranking or weighting operational objectives (Saaty, 1977).

As per Drake (1998), there are four main steps in structuring an AHP model:

1- Selection of criteria.
2- Evaluation of the relative importance of these criteria using pairwise comparisons.
3- Evaluation of each alternative relative to each other on the basis of each selection criteria using the pairwise comparison technique.

4- Combination of the ratings acquired in steps 2 and 3 to obtain an overall relative rating for each alternative.

The selection of criteria will help cultivate the AHP graphical illustration for the investigated problem in terms of the main goal, criteria, and alternatives (Anderson et al., 2008). After developing the AHP model, the decision maker can appoint the preference of each decision's alternatives in accordance with each sub goal's criteria' (Anderson et al., 2008). This means that the weight and the relative importance of each element in the hierarchy can be obtained through a pairwise comparison method (Ramin et al., 2012) using preference scales. Therefore, decision alternatives can be prioritised in ranking form following a mathematical calculation used to synthesise the information and preferences of each criterion and alternatives, permitting a quantitative interpretation of the judgement among these attributes (Pillay and Wang, 2003).

Saaty developed the AHP method in 1965. The AHP method rates lies on a scale from 1, which represents 'Equally important', to 9, which represents 'Extremely important' (see Table 4.1) (Saaty, 1980; Sarkis and Talluri, 2004).

Table 4.1. 9-point intensity of relative importance scale (Saaty, 2008)

Intensity of Relative Importance	Definition
1	Equal Importance
3	Moderate Importance of one over another
5	Essential or strong importance
7	Demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values between the two adjacent judgments

According to the above table, if the importance degree of a factor 'A' compared to 'B' is given, then the importance of 'B' is reciprocally compared to 'A'. Therefore, weighting the importance of quantifiable or non-quantifiable sets of information can be expressed either by ratio scale or verbally (Pohekar and Ramachandran, 2004).

4.3.2.1 AHP algorithms

According to Anderson et al. (2008), it is essential to develop a pairwise comparison matrix to determine factors' priorities. This matrix, which is represented by n-by-n and called matrix D, quantifies experts' judgments on $A_i$and A_j pairs of attributes. The a_{ij} entries are determined by the following rules:

Rule 1. If $a_{ij} = \alpha$, then $a_{ij} = 1/\alpha, \alpha \neq 0$.

Rule 2. If $A_i$is decided to be of equal relative importance as A_j, then $a_{ij} = a_{ji} = 1$.

It is important to mention that the average values configuring the matrix are based on three experts' opinions (Saini and Kumar, 2014). Accordingly, matrix D can be constructed based on the above rules, as shown on equation 4.1

$$D = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{1n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \qquad (4.1)$$

Where $i, j = 1,2,3, \dots \dots \dots, n$ and each a_{ij} is the relative importance of characteristic $A_i$to characteristic A_j.

In 1977, Satty used a theory called the Perron-Frobenius theory, which was created in 1960 by Gantmacher to ensure the existence of one of the largest real positive eigenvalues for a matrix D with positive entries whose associated eigenvector is the vector of weights. This normalised weight vector was unique in having its entries amount to a unit (Saaty, 1977). Therefore, in the lowest hierarchy level activity, the vector of weights associates with the next level criterion and can be derived by a pairwise comparison matrix with respect to that criterion (Saaty, 1994). By recording a compared quantified judgment on

(A_i, A_j) pairs as a numerical entry as a_{ij} in matrix D, it is essential to assign a numerical weight $\omega_1, \omega_2, \ldots \omega_n$ to the n contingences $A_1, A_2, \ldots\ldots, A_n$ to reflect that recorded quantified judgment. Thus, to calculate the weight, Pillay and Wang (2003) used the following equation:

$$w_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (i = 1,2,3, \ldots\ldots, n) \tag{4.2}$$

Where a_{ij} characterises a comparison matrix of order n by the input of rows $i\ and\ j$.

When various numbers of a pairwise comparison are weighed, inconsistent values were expected. The AHP method provides a consistency measure – Consistency Index (CI) and Consistency Ratio (CR) – for any given set of pairwise comparisons (Riahi et al., 2012; Ung et al., 2006) as shown in equations 4.3 and 4.4. When the CR indicates that the value of the pairwise comparison for matrix D is less than or equal to 0.1, the consistency of the pairwise comparison is reasonable and can be used (Andersen et al., 2008; Yang et al., 2011; Riahi et al., 2012). However, if the CR indicates more than 0.1, then the decision makers should consider revising the pairwise judgement due to inconsistency. Moreover, equation 4.5 can calculate the maximum weight λ_{max} for the $n - by - n$ comparison matrix D.

$$\lambda_{max} = \frac{\sum_{j=1}^{n}\left[\left(\sum_{i=1}^{n} w_i a_{ji}\right)/w_j\right]}{n} \tag{4.3}$$

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{4.4}$$

$$CR = \frac{CI}{RI} \tag{4.5}$$

Where:

CR is the consistency ratio

CI is the consistency index

RI is the average random index (Table 4.2)

n is the matrix order

λ_{max} is the maximum weight value of the $n-by-n$ comparison matrix D.

Table 4.2. Value of RI versus matrix order (Saaty, 2013)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

RI: average random index

4.3 Empirical application of DT and AHP

This section examines the feasibility of the identifiable criteria that the researcher highlighted following the discussions conducted with the three groups through the interviews in chapter three. The identifiable factors are based on a qualitative process, which will be examined using the Delphi method, and aims to seek agreement among experts on these identifiable factors. This analysis will be followed by the use of AHP as a decision-making technique to prioritise these factors according to the degree of importance in significantly influencing the reliability of operations. Therefore, this section will highlight the process data collection that fits the methods used to achieve this research objective.

4.3.1 Pilot study for Delphi method

The researcher developed an initial survey based on the results obtained via group interviews conducted in chapter three. Although the researcher discussed in detail each selected criterion highlighted by the experts, the researcher must give an operational definition of each essential, highlighted criterion to assess the reliability of the pilot (see Table 4.3). Since variance in operators' perceptions was observed during discussions, this process will help clarify the meaning of factors that built the criterion and make it available to all participants at all times. Accordingly, the developed questionnaire was sent to five senior pilots with master licences and pilotage experience in three different countries and nationalities beyond where this study was conducted. The returned comments were valuable in order to ensure the rationality of the questionnaire. Some minor clarification was asked along with minor amendments. The researcher amended the comments and the questionnaire was ready to send out for round one.

Table 4.3. Operational definitions for alternatives

Level 1	Level 2	Level 3	Factors shaping Level 3	Sources
Goal	Shaping factors	Sub-factors	Sub-factor Index	
Marine Pilot Reliability Index (MPRI)	1. TP	1.1. QPL	A set of competencies (educational level, licences and certifications) that exhibit his/her achievement in order to comply with the minimum work-related knowledge required to carry out certain duties.	Port accident case 1 (see section 3.7.3); Experts interviews; IMO, 2004; Riahi et al., 2012
		1.2. ST	A set of compulsory or additional work-related courses and refresher training required to maintain the minimum operational standard.	Expert interviews; Alvarenga et al., 2014; Berg, 2013
		1.3. WEx	The accumulation of knowledge or skills gained over time as a pilot.	Expert interviews; Yule and Brown, 2012;
	2. PF	2.1. WH	The number of working hours per day or the time of the day when the operator is carrying out his/her duty.	Port accident cases 2 and 4 (see section 3.7.3); Experts interviews; Kim et al., 2009; Hetherington et al., 2006; Raby and McCallum, 1997
		2.2. WS	Commercial and economic stresses, management stresses, work-related demand, high level of traffic, management style, etc.	Field observation (see section 3.7.1); Port accident cases 2 and 4 (see section 3.7.3); Josten et al., 2003; Flin et al., 2003
		2.3. WEnv	Physical working environment, ergonomic design, the status of the operative's environment.	Field observation (see section 3.7.1); James and Walters, 2002; Bhattacharya and Tang, 2013
	3. NTS	3.1. DM	Encompasses a set of structural sequences that includes defining and diagnosing problems, generating options, assessing risks and option selection through different available alternatives, followed by an outcome review.	Port accident case 1 and 4 (see section 3.7.3); Moorthy et al., 2005; Sharma et al., 2011
		3.2. SA	Is the perception of elements in the current situation through information gathering, followed by assessing the significance of the information gathered from different resources to form a clear picture to implement a procedure for the current operational event, and finally implement the necessary action to avoid an unfavourable event.	Field observation (see section 3.7.1); Port accident cases 1, 2, 3 and 4 (see section 3.7.3); Fletcher et al., 2004; Saeed et al., 2016
		3.3. CS	Is the ability of a member to regulate, control, motivate, express feelings and convey information to other team members involved in an operation.	Field observation (see section 3.7.1); Port accident cases 3 and 4 (see section 3.7.3); Flin et al., 2008; Salmon et al., 2009; Blundel, 2004
		3.4. T&L	Is the way to establish a clear two-way channel of communication, openness to criticism, empathy towards cultural diversity, capability to motivate people and develop a community atmosphere, cope with an operator's limitations, and be a key team player.	Field observation (see section 3.7.1); Port accident cases 1, 2, 3 and 4 (see section 3.7.3); Combe and Carrington, 2015; Little, 2004; Sasou and Reason, 1999
	4. F&S	4.1. OA	As an operator gains work-related experience, he/she is getting older. Operator age can indicate how the performance of an experienced operator changes over time. For example, a reduction in physical capacities and coordination, flexibility, strength and power can be expected when getting older.	Port accident case 2 (see section 3.7.3); Kim et al., 2009; Josten et al., 2003
		4.2. HI	This has been identified as a factor that is strongly associated with accidents at sea. It can be a result of the nature of the work, geographical location, stresses at work, prolonged working hours, commercial pressure and organisational culture as well as historic family illness.	Expert interviews; Sturman, 2002; Josten et al., 2003
		4.3. BS	Pilots are required to maintain a high level of body strength, as they need to climb a ladder from time to time, this will be followed by a high level of cognitive demand required to guide the ship safely during pilotage operations. Any reduction in body strength will affect a pilot's ability to work effectively and limits cognitive ability.	Expert interviews; Wadsworth et al., 2008; Mohren et al., 2001

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength))

4.3.2 Delphi round one

The first Delphi questionnaire, along with the participant information sheet (PIS) and an invitation letter, was transmitted electronically through SurveyMonkey to allow participants to access the survey through their personal devices. The researcher benefited from the conducted group interviews by accessing the personal details given by the experts after they expressed their willingness to participate through to the end of this study and as highlighted in chapter three. This support eased the process of collecting essential data needed for this round via sending direct emails to the experts and using phone calls as reminders. The questionnaire link was sent directly through email to all participating pilots, forming the panel members, which consisted of 35 pilots with varying and considerable working experience. The panellists were asked to access the survey through the given link and read the PSI before answering the questions. The main objective of the PSI was to gain an overview of the participants with a key element and the objective from conducting this research. Although this information is known from previous qualitative analysis steps, it was essential to present it to the participants again to make sure they understand the study's main purpose. Moreover, participants were given the chance to accept or reject the survey at any stage. In addition, participants were required to tick an implied consent field to proceed to accessing the questions. The first questionnaire round was completed by the 35 pilots participating in the interview. The demographic characteristics of the Delphi expert panel are presented in Table 4.4. It is apparent from the demographic distribution of participants that a higher number of participants – 19 – have maritime diplomas along with a pilot licence, followed by three, seven, and nine pilots with third, second, and master's mariner degrees along with a pilot licence respectively. The first demographic characteristics represent gender, revealing that 100% are male. There is almost equal distribution among the four groups in terms of age, except for the 60 and over group. Pilots falling within the 20-29 and 50-59 age groups are comprised of nine pilots each, while the age groups 30-39 and 40-49 are comprised of eight pilots each; finally, the age group over 60 consists of only one pilot. This distribution could benefit this study as proven by different literature studies that show that variance in operators' perception, safety-related issues, ability to learn new things, and experience were observed among different age groups in different fields. Moreover, the importance of identified criteria can be highlighted and stressed differently if compared between different participants' age groups. However, the third participant characteristic is the pilot rank. The majority of the participants were ranked as first pilots, with 22 pilots representing 63% of the total number of participants followed by numbers of six, five, and two pilots representing second, third, and trainee pilots respectively. In addition, the pilot experience represented the fourth demographic characteristic, reflecting, 13 and a majority of pilots have more than 20 years of experience. Nonetheless, pilots with five years or less of experience represent the second highest pilotage experience. These two main characteristics provide reasonable operational opinions, since the majority of pilots have pilotage experience of more than 20 years and are ranked as seniors. Moreover, this advantage can result in valuable comments and reflect a real operational picture, since these pilots have prolonged operational experience and stabilised mental opinions. More importantly, the total number of experts distributed based on the above main demographic characteristics, in accordance with their qualification/pilotage license or category, shows the majority of participants (54%) having a diploma with a pilotage license (see figure 4.2). The participants' qualifications were distributed among the above four main demographic characteristics and presented in figures 4.3-4.5.

Table 4.4. Delphi Experts' demographic summary

Expert characteristics		Frequency (N=35)					
		Participant qualification/category					
		Dip. +PL	3rd +PL	2nd +PL	1st +PL	Master +PL	Total (%)
Gender	Male	19	3	7	0	6	**35** (100%)
	Female	0	0	0	0	0	**0** (0%)
	Total	**19 (54%)**	**3 (9%)**	**7 (20%)**	**0 (0%)**	**6 (17%)**	**35 (100%)**
Age Group	20 - 29	8	1	0	0	0	**9** (25.7%)
	30 – 39	3	2	2	0	1	**8** (22.9%)
	40 – 49	3	0	3	0	2	**8** (22.9%)
	50 – 59	5	0	2	0	2	**9** (25.7%)
	60 and above	0	0	0	0	1	**1** (2.8%)
	Total	**19 (54%)**	**3 (9%)**	**7 (20%)**	**0 (0%)**	**6 (17%)**	**35 (100%)**
Pilot's Rank	Trainee Pilot	0	0	1	0	1	**2** (6%)
	Third Pilot	4	1	0	0	0	**5** (14%)
	Second Pilot	3	2	1	0	0	**6** (17%
	First Pilot	12	0	5	0	5	**22** (63%)
	Total	**19 (54%)**	**3 (9%)**	**7 (20%)**	**0 (0%)**	**6 (17%)**	**35 (100%)**
Pilotage Experience	≤ 5 Years	8	0	2	0	1	**11** (31%)
	6 – 10 Years	3	3	0	0	2	**8** (23%)
	11 – 15 Years	0	0	1	0	1	**2** (6%)
	16 – 20 Years	0	0	1	0	0	**1**(3%)
	> 20 Years	8	0	3	0	2	**13** (37%)
	Total	**19 (54%)**	**3 (9%)**	**7 (20%)**	**0 (0%)**	**6 (17%)**	**35 (100%)**

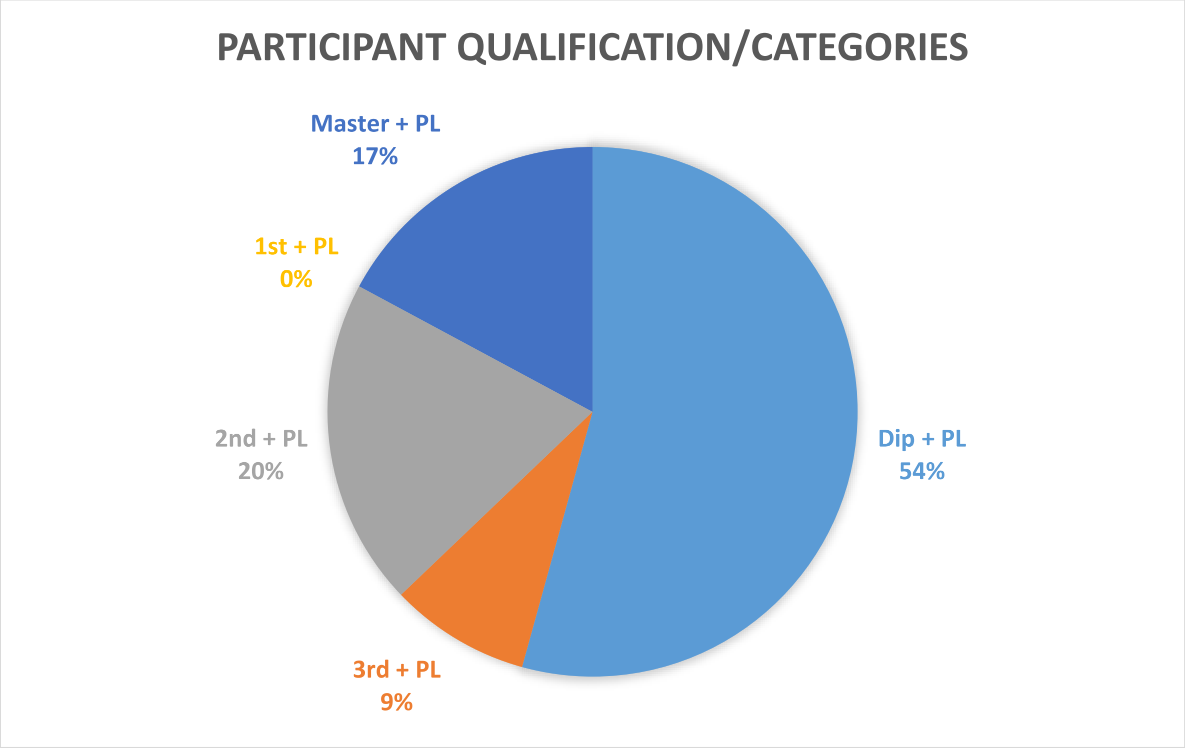

Figure 4.2. Participant qualification/categories

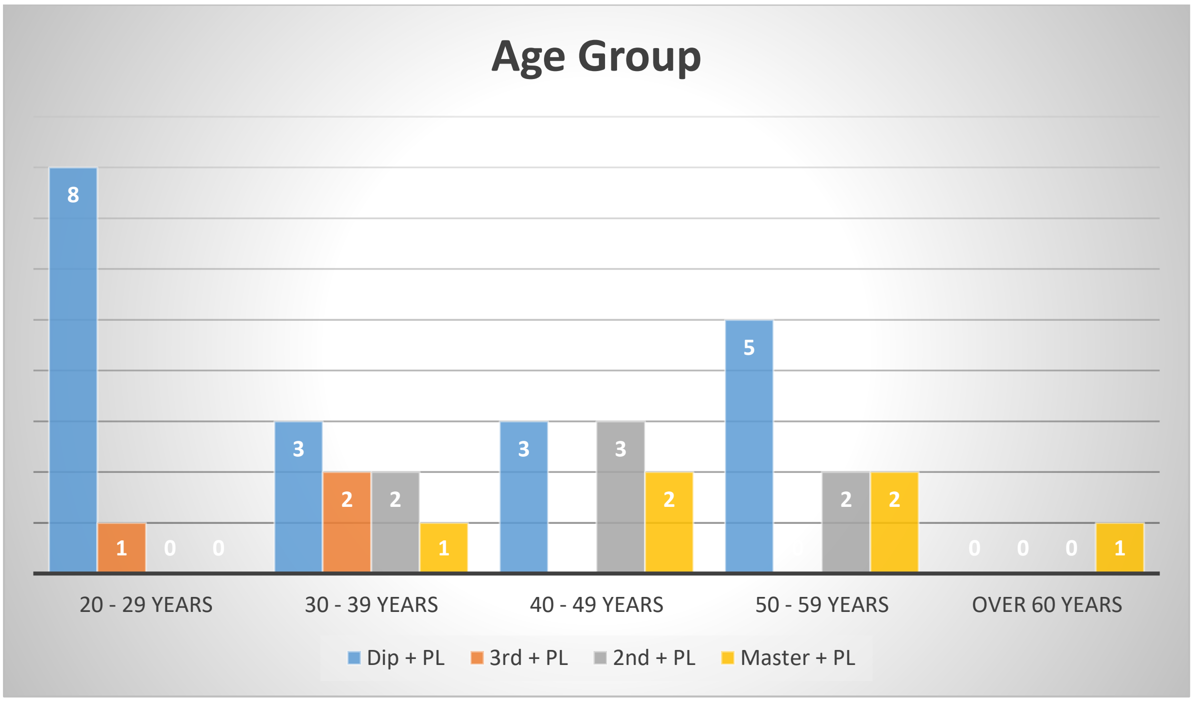

Figure 4.3. Participant age group/qualification

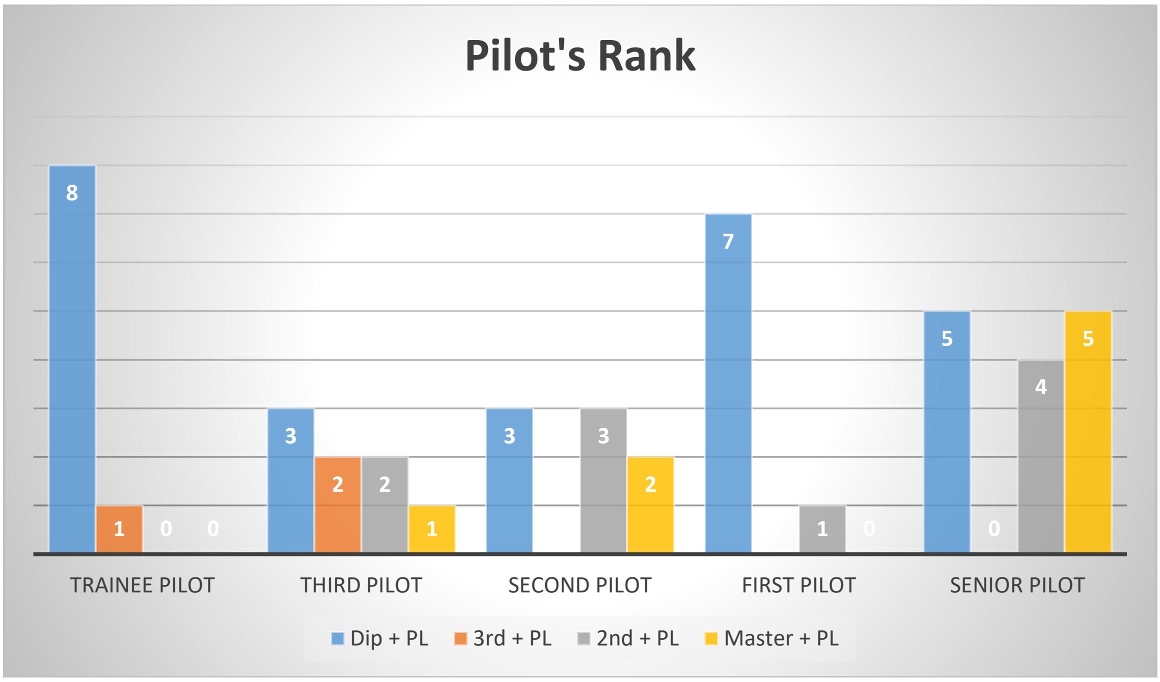

Figure 4.4. Pilot’s rank/qualification

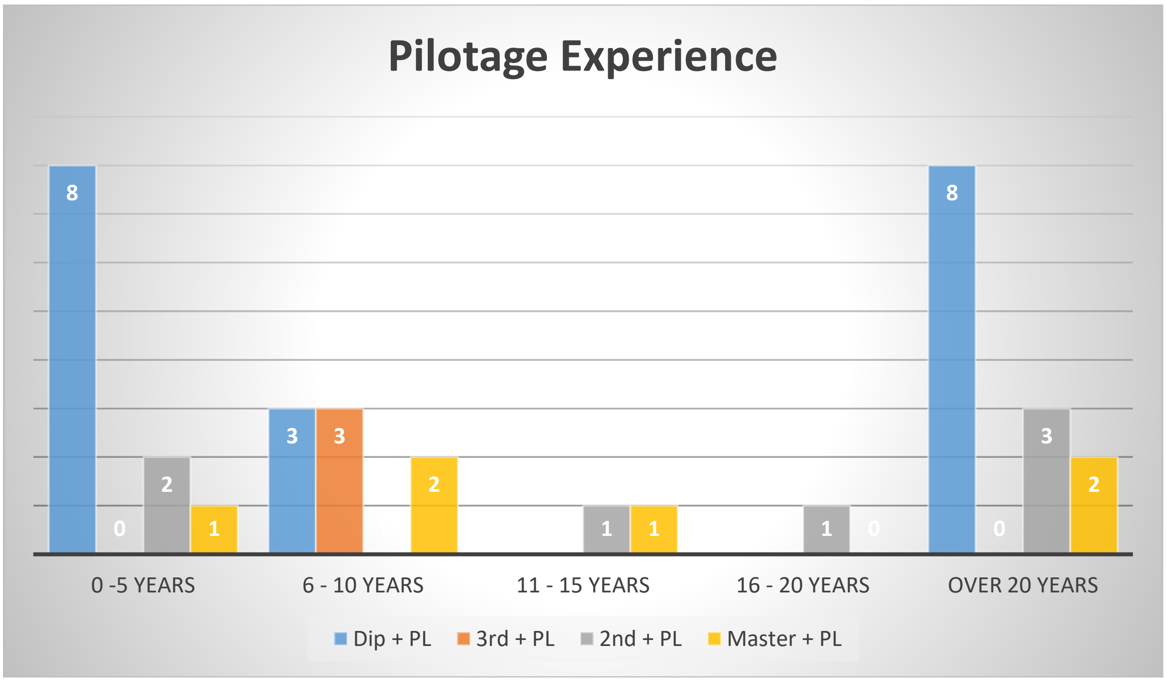

Figure 4.5. Pilot’s experience/qualification

In round one, the panel members were asked to rate the degree of importance to each identifiable criterion using a five-point Likert scale, where 1 represents not important at all and 5 represents significantly important. The Likert scale was treated as interval data, used to analyse and calculate participants’ ratings (Clayton, 1997). Accordingly, a numerical degree of consensus among highlighted criteria was measured to increase objectivity and comparable degree of consensus (Redmond et al., 2006). Faherty (1979) suggested that using the median and inter-quartile range is essential for analysing data and statistical feedback for the collected data obtained by Delphi rounds. Thus, for each identifiable criterion, the median and the inter-quartile range were calculated.

According to the experts' responses, the researcher computed the rating statistics for each identifiable criterion that constituted the developed marine pilots' reliability index (MPRI). The experts' responses from the first round were presented in Table 4.5, showing the median (Med) and the inter-quartile range (IQR). Criteria that reached the 'Med' level 'Med' of 4 or more and IQRs of 1 or less were considered a consensus and agreed upon by participants as important. The 'Med' and IQR ranges obtained from the first round are summarised in Table 4.5.

In this study, the expert panel members ranked the degree of agreement and the importance of each proposed reliability indicator using the Likert five-point scale. Accordingly, the researcher calculated the given responses from the 35 experts using statistical methods for each proposed reliability indicator. Table 4.5 shows the experts' opinions in round one by listing the proposed reliability indicator with medians, averages, and inter-quartile ranges (IQR). If any of these indices are not important or agreed upon, this index will be highlighted and underlined in **bold** font. If the median of an index is valued to four or greater and the IQR one or less, this index is important and achieves consensus and will not be highlighted in bold or even underlined.

The results obtained in this study surprisingly, showed that experts agreed that all proposed MPRIs are important, achieving an adequate consensus level from round one (see Table 4.5). This result could be justified because the participants were involved in the interviews. In addition, the researcher successfully identified the main concerns that the marine pilot highlighted and presented as significant criteria; this set of criteria may have confirmed the reliability of the results. Moreover, the researcher's investigation and analysis of the literature were to some extent proven adequate since the results from round one achieved consensus. Accordingly, the results from round one show that the importance degree of all the MPRIs exceeded the agreed threshold of the suggested median. Moreover, the entire reliability indicator exceeded the threshold for a consensus on distribution. This means that there is no need to change any operational definition or add any additional indicator for the second round questionnaire. The minimum number of rounds proposed by previous studies is two, so the second round aims to display the participant positions based on their opinions compared to the expert panel. Therefore, the experts have the choice to reconsider their answers or keep the same opinion, as explained in next section.

Table 4.5. Round-one panel opinions

Reliability indicator (Likert scale from 1 to 5)	Panel opinions			
	n	Med	Aver.	IQR
Operator Qualifications	35	4	3.8	1
Specific Training	35	5	4.5	0
Working Experience	35	5	4.5	0
Working Hours	35	4	4.2	0
Work Stresses	35	4	4.3	0
Working Environment	35	4	4.1	0
Decision-Making	35	5	4.5	0
Situation Awareness	35	4	4.2	0
Communication Skills	35	4	4.1	0
Teamwork and Leadership	35	4	4.03	0
Operator Age	35	4	3.77	1
Health Issues	35	4	4.23	0
Body Strength	35	4	3.77	1

Likert scale used (1=not at all important and 5= very important)
n: the number of participants
Med: median; Aver.: the average; IQR: the inter-quartile range

4.3.3 Delphi round two

The questionnaire for the second round followed the quantitative data analysis from the first round. The inclusion of statistical data obtained from the first round is a feature of the second round questionnaire: the panel members' ratings of importance levels and consensus were presented in a new questionnaire version. As the first round found consensus and there was no additional criterion to add, this questionnaire round included the same MPRIs along with the statistical results from the first round, which were sent back to the same experts showing their answers along with the group answer. This step aimed to encourage experts with different answers from the group to justify their choices.

The second round started by inviting participants from round one (n=35) to participate in the second round. The panellists were encouraged to rate every reliability indicator using the same procedure from round one using Likert 5-point scale. This questionnaire presented the median, average, and the IQR for every reliability indicator from the previous round. The reason for presenting these factors was to ask experts if they would reconsider the answers or explain their dissenting choices in the comment box. Response variations were justified, as the discussion conducted during the group interviews showed variance on experts' opinions. This was confirmed within this experimental process, as selection variants were observed across experts' feedback on Delphi rounds.

In this round, every participant was sent a questionnaire by email with his original answers to maintain confidentiality. During the previous round, the questionnaires were transmitted electronically via SurveyMonkey to allow participants to easily access them. However, this round required a follow-up email reminder to encourage participants to return the questionnaire by the deadline, stipulated to be accomplished within two weeks. This process was a success, as the experts' panel in round two answered the second round survey. Therefore, in round two, the 35 participants represented 100% of the total participants from round one. The results obtained from this round are stated in Table 4.6. The consensus among the group for the identified MPRIs were achieved from the first round and the second round conducted with the Delphi method, which requires at least two rounds. However, the second round, as previously mentioned, encouraged participants to compare their answers with the group and update or justify their choices. Accordingly, Table 4.6 represents both Delphi rounds and highlights in red font the improved M, Aver., and IQR.

Following this process, the researcher developed the hierarchy structure of the proposed MPRIs, aiming to assign the weight of each identifiable criterion using AHP.

Table 4.6. Round two panel opinions

Reliability indicator	Panel opinions						
(Likert scale from 1 to 5)	n	Med (R1)	Med (R2)	Aver. (R1)	Aver. (R2)	IQR (R1)	IQR (R2)
Operator Qualifications	35	4	4	3.8	4.1	1	0
Specific Training	35	5	5	4.5	4.7	0	0
Working Experience	35	5	5	4.5	4.7	0	0
Working Hours	35	4	4	4.2	4.4	0	0
Work Stresses	35	4	5	4.3	4.5	0	0
Working Environment	35	4	4	4.1	4.3	0	0
Decision-Making	35	5	5	4.5	4.6	0	0
Situation Awareness	35	4	5	4.2	4.5	0	0
Communication Skills	35	4	4	4.1	4.4	0	0
Teamwork and Leadership	35	4	4	4.0	4.3	0	0
Operator Age	35	4	4	3.8	3.8	1	1
Health Issues	35	4	4	4.2	4.4	0	0
Body Strength	35	4	4	3.8	4	1	0

4.3.4 AHP application to field investigation

As mentioned above, the main objective of utilising the AHP method is to enable the decision-makers to find relative weights of risk factors and determine the most significant one to select the best alternatives for different criteria. Showing the importance of each criterion is extremely important in this study. These important judgements are based on experts' points of view. The pilots who participated in this research assigned the relative importance to each criterion by filling in a questionnaire designed for the AHP method (see Appendix I). The participants were encouraged by the marine department to participate through the end of this study and were reminded by emails to return the questionnaire. Therefore, all the questionnaires were returned.

However, let us assume that, $A_1, A_2, A_3,$ and A_4 represent decision-making, situation awareness, communication, teamwork, and leadership respectively. Based on the given information, matrix D was developed. This is followed by the application equations 4.1-4.5, which were applied to calculate the weight for each criterion to assign weight to each sub-criterion.

After receiving the complete questionnaires from all the participants, the hierarchy criteria were weighted by applying AHP equations 4.1-4.5 as follows:

The following pairwise comparison matrix 4×4 was constructed to obtain the weight of NTS sub-criteria as a sample of the calculation process:

	Decision-making	Situation awareness	Communication Skills	Teamwork & leadership
Decision-making	1 (a_{11})	0.35 (a_{12})	0.21 (a_{13})	0.23 (a_{14})
Situation awareness	2.85 (a_{21})	1 (a_{22})	0.40 (a_{23})	0.40 (a_{24})
Communication Skills	4.73 (a_{31})	2.5 (a_{32})	1 (a_{33})	1.22 (a_{34})
Teamwork & leadership	4.44 (a_{41})	2.52 (a_{42})	0.82 (a_{43})	1 (a_{44})

In the first step, we need to form matrix D, as follows:

$$D = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} = \begin{bmatrix} 1 & 0.35 & 0.21 & 0.23 \\ 2.84 & 1 & 0.40 & 0.40 \\ 4.73 & 2.50 & 1 & 1.22 \\ 4.44 & 2.52 & 0.82 & 1 \end{bmatrix}$$

The second step is to calculate the weight of each criterion by applying the rule in Equation 4.2:

$w_k = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{kj}}{\sum_{i=1}^{n}a_{ij}}$ $(k = 1,2,3, \ldots\ldots, n)$, and $n = 4$, as follow:

$$W_{DM} = \frac{1}{4}\left[\left(\frac{a_{11}}{a_{11}+a_{21}+a_{31}+a_{41}}\right)+\left(\frac{a_{12}}{a_{12}+a_{22}+a_{32}+a_{42}}\right)+\left(\frac{a_{13}}{a_{13}+a_{23}+a_{33}+a_{43}}\right)\right.$$
$$\left.+\left(\frac{a_{14}}{a_{14}+a_{24}+a_{34}+a_{44}}\right)\right]$$

$$W_{DM} = \frac{1}{4}\left[\left(\frac{1}{1+2.84+4.73+4.44}\right)+\left(\frac{0.35}{0.35+1+2.5+2.52}\right)\right.$$
$$\left.+\left(\frac{0.21}{0.21+0.40+1+0.82}\right)+\left(\frac{0.23}{0.23+0.40+1.22+1}\right)\right]$$

W_{DM} = 0.0747

$$W_{SA} = \frac{1}{4}\left[\left(\frac{a_{21}}{a_{11}+a_{21}+a_{31}+a_{41}}\right)+\left(\frac{a_{22}}{a_{12}+a_{22}+a_{32}+a_{42}}\right)+\left(\frac{a_{23}}{a_{13}+a_{23}+a_{33}+a_{43}}\right)\right.$$
$$\left.+\left(\frac{a_{24}}{a_{14}+a_{24}+a_{34}+a_{44}}\right)\right]$$

$$W_{SA} = \frac{1}{4}\left[\left(\frac{2.84}{1+2.84+4.73+4.44}\right)+\left(\frac{1}{0.35+1+2.5+2.52}\right)\right.$$
$$\left.+\left(\frac{0.40}{0.21+0.40+1+0.82}\right)+\left(\frac{0.40}{0.23+0.40+1.22+1}\right)\right]$$

W_{SA} = 0.1701

$$W_{CS} = \frac{1}{4}\left[\left(\frac{a_{31}}{a_{11}+a_{21}+a_{31}+a_{41}}\right)+\left(\frac{a_{32}}{a_{12}+a_{22}+a_{32}+a_{42}}\right)+\left(\frac{a_{33}}{a_{13}+a_{23}+a_{33}+a_{43}}\right)\right.$$
$$\left.+\left(\frac{a_{34}}{a_{14}+a_{24}+a_{34}+a_{44}}\right)\right]$$

$$W_{CS} = \frac{1}{4}\left[\left(\frac{4.73}{1+2.84+4.73+4.44}\right)+\left(\frac{2.50}{0.35+1+2.5+2.52}\right)\right.$$
$$\left.+\left(\frac{1}{0.21+0.40+1+0.82}\right)+\left(\frac{1.22}{0.23+0.40+1.22+1}\right)\right]$$

W_{CS} = 0.3989

$$W_{T\&L} = \frac{1}{4}\left[\left(\frac{a_{41}}{a_{11}+a_{21}+a_{31}+a_{41}}\right)+\left(\frac{a_{42}}{a_{12}+a_{22}+a_{32}+a_{42}}\right) + \left(\frac{a_{43}}{a_{13}+a_{23}+a_{33}+a_{43}}\right)+\left(\frac{a_{44}}{a_{14}+a_{24}+a_{34}+a_{44}}\right)\right]$$

$$W_{T\&L} = \frac{1}{4}\left[\left(\frac{4.44}{1+2.84+4.73+4.44}\right)+\left(\frac{2.52}{0.35+1+2.5+2.52}\right) + \left(\frac{0.82}{0.21+0.40+1+0.82}\right)+\left(\frac{1}{0.23+0.40+1.22+1}\right)\right]$$

$W_{T\&L}$ = 0.3563

The third step is to find the Consistency Ratio (CR), by Equation 4.5. This step is required to find λ_{max}, using Equation 4.3, and the Consistency Index (CI), using Equation 4.4. Therefore $\lambda_{max} = \frac{\sum_{j=1}^{n}[\sum_{k=1}^{n} w_k a_{jk}/w_j]}{n}$, and the Consistency Index

CI = $\frac{\lambda_{max}-4}{4-1}$

$$\lambda_{max} = \frac{w_1a_{11}}{w_1}+\frac{w_2a_{12}}{w_1}+\frac{w_3a_{13}}{w_1}+\frac{w_4a_{14}}{w_1}+\frac{w_1a_{21}}{w_2}+\frac{w_2a_{22}}{w_2}+\frac{w_3a_{23}}{w_2}+\frac{w_4a_{24}}{w_2}+ \frac{w_1a_{31}}{w_3}+\frac{w_2a_{32}}{w_3}+\frac{w_3a_{33}}{w_3}+\frac{w_4a_{34}}{w_3}+\frac{w_1a_{41}}{w_4}+\frac{w_2a_{42}}{w_4}+\frac{w_3a_{43}}{w_4}+\frac{w_4a_{44}}{w_4} =$$

λ_{max}=

[1+0.7965+1.1209+1.0966+1.2480+1+0.9383+0.8381+0.8861+1.0658+1+1.0897+0.9313 +1.2028+0.9181+1] = 16.13

Therefore, $\lambda_{max} = \frac{\sum_{j=1}^{n}[\sum_{k=1}^{n} w_k a_{jk}/w_j]}{n} = \frac{16.13}{4}$ = 4.03

Then, CI = $\frac{4.03-4}{4-1}$ = 0.011

Therefore, Equation 4.5, CR = $\frac{CI}{RI}$, where the RI can be obtained from (Table 4.2)

CR = $\frac{0.011}{0.9}$ = 0.012

However, if the CR is greater than 0.10, there is inconsistency in the pairwise judgements, which must be reviewed by the decision-makers before taking an additional step (Riahi et al., 2012). This means that if the CR is equal to or less than 0.1, it is considered reasonable for such a comparison, which allows the AHP to proceed further to calculate the weight. In this research, the returned questionnaires were inconsistent for 24 of the returned questionnaires. Thus, it was essential to reconsider those participants' answers until reaching consistency. Those participants were provided with an explanation on how to ensure consistency when answering the questionnaire (see AHP questionnaire in Appendix I). Therefore, the assigned pilots were asked to reconsider their opinions until the appropriate level of consistency was achieved. Because of the above experts' evaluations, the consistency ratio was found reasonable to proceed to weight calculation for each criterion. The information collected from the pilots was entered into a software package called AHP calc. version 12.08.13, and the weight for each criterion, sub-criterion, and even sub-sub-criterion was evaluated.

Based on the data analysis, the reliability of the marine port pilotage operation was dependent on many participants. According to the experts' opinions, the pilot was ranked the most important factor in the operation, as shown on Table 4.7, with a relative weight of 0.36, followed by the tug master and the ship master, with relative weights of 0.25, and 0.15, respectively. The harbour master and the VTS operator where ranked fourth and fifth with relative weights of 0.15 and 0.09, respectively. Each of those participants are subjected to different variables that shape their reliability, and changes of variable value will eventually change the reliability of the pilots and teamwork. This research focused on assessing the reliability of a marine port pilot. Criteria that shape marine pilot reliability were ranked using AHP based on the experts' opinions as shown in Table 4.8. The results show the local weight of each criterion using the AHP method to identify the independent relative weights for each of the MPRI's. The participants in this research ranked the four main criteria that were identified as central to shaping operator reliability as follows: PF (0.4451), NTS (0.3643), TP (0.1154), and F&S (0.0751). The following outlines the beliefs of experts involved in this research on the degree of importance of these main criteria in shaping reliability. Factors constituting operators' TP are: QPL, ST, and WEx. The AHP method was used to ranked the degree of importance with ST (0.4518), WEx (0.3651), and QPL (0.1832). Similarly, factors constituting PF were ranked from highest to lowest as follows: WS (0.5472), WEnv (0.3394), and WH (0.1134). In addition, factors constituting NTS were ranked as follows: CS (0.3996), T&L (0.3573), SA (0.1690), and DM (0.0740). Lastly, factors constituting operator F&S were ranked as follows: BS (0.6847), HI (0.2041), and OA (0.1112). Global weights were identified to highlight the degree of influence of each criterion on marine pilot reliability. For instance, ST was ranked as the most significant factor in shaping marine pilot TP with a value of 0.4518, while ST ranked as the sixth most significant factor in shaping pilots' reliability with a global weight value of 0.052. The distinction between the local weight and global weight is that the local weight represents the significance of that particular criterion in shaping the associated upper level criterion (i.e. TP), while the global weight represents the degree of influence of the criterion on overall reliability. The top five factors found significant in shaping the reliability of a marine pilot are WS, WEnv, CS, T&L, and SA, from most to least significant. The identified weights presented in Table 4.8 are used in the following chapters to prioritise factors that significantly affect the reliability of the pilotage operation. However, for this time-constrained research, the researcher focused on the pilot and left other factors involved in the pilotage operation for further investigation.

Table 4.7. Pilotage operation main criteria

Main Criteria	Weights	Importance Rank
Pilot	0.362	1
Ship Master	0.151	3
Tug Master	0.250	2
VTS Operator	0.089	5
Harbour Master	0.148	4

Table 4.8. Pilot’s Sub-Criteria

Goal	Sub-level	MPRIs	LW	Ranking	GW	Ranking
Pilot Reliability	**TP** (0.115)	**QPL**	0.183	3	0.021	11
		ST	0.452	1	0.052	6
		WEx	0.365	2	0.042	9
	PF (0.445)	**WH**	0.113	3	0.050	8
		WS	0.547	1	0.243	1
		WEnv	0.340	2	0.151	2
	NTS (0.364)	**DM**	0.074	4	0.027	10
		SA	0.169	3	0.062	5
		CS	0.400	1	0.146	3
		T&L	0.357	2	0.130	4
	F&S (0.075)	**OA**	0.111	3	0.008	13
		HI	0.204	2	0.015	12
		BS	0.685	1	0.051	7

4.4 Conclusion

Human errors were the most significant factors in marine port pilotage operation as shown in the previous chapters, the interviews, accident analyses, and field observations. Furthermore, the marine port pilotage operation is a series network subjected to the reliability of its main teamwork. The marine pilot is one of the team of workers conducting the marine pilotage operation, and the reliability of marine port pilotage service can be evaluated through the reliability evaluation of its participants.

Therefore, in this chapter and with the support of the literature review, the criteria identified from Chapter 3 were examined for consensus based on experts’ opinions of these criteria. These criteria identify the main, significant criteria that influence the reliability of a marine port pilot as the main driver proposed for this research. The DT was used for two questionnaire rounds confirming agreement among the participants for the identified criteria highlighted through the data analysis in Chapter 3. Moreover, the experts were encouraged to assign weights to every identifiable criterion using AHP.

As revealed in this chapter, the proposed MPRI to evaluate the reliability of a marine pilot was found dependent upon many variables, and the value of a criterion will change the reliability of a pilot and team workers. The proposed methodology confirms the significance of the identified criteria and weights each criterion considered essential to assessing the reliability of a marine pilot. However, it is important to identify the degree of dependencies between criteria. During the interviews, the researcher discussed dependent and independent relations among team workers and variables that constituted an operator’s performance.

Chapter Five: A proposed hybrid methodology to preference the developed Marine pilot reliability indices (MPRIs) using a fuzzy decision-making trial and evaluation laboratory (FDEMATEL) and an analytical network process (ANP)

5.1 Chapter Summary

Obtaining higher reliability requires careful monitoring and evaluation of the identified criteria highlighted in previous chapters. In this study, marine pilots were subjected to higher operational demands that affected their ability to maintain safer and reliable operational standards. Identifying an effective reliability evaluation and the most significant reliability influence was the goal of the first stage. Accordingly, assigning the weight to each identified reliability indicator was essential in developing a rational decision and a precise reliability evaluation tool. Identified Marine pilot reliability indices (MPRIs) are usually presented in a hierarchical structure, but this can complicate the identification of criteria. This study takes into account independent influences and interdependencies between MPRIs using Multi-Criteria Decision Making (MCDM) techniques. The MCDM is now widely used among scholars for solving various problems where different criteria are involved. This chapter aims to highlight the degree of interdependency among the identified criteria highlighted in previous chapters. The analytical hierarchy process (AHP) was used to assign interdependency among the criteria followed by assigning the local weight. However, the interdependent relationship between factors can be obtained using a fuzzy decision-making trial and evaluation laboratory (FDEMATEL) in order to assign the global weights to each criterion using an analytical network process (ANP). This work has successfully identified the interdependencies among the criteria and assigned the weight amongst the factors in order to carry further examination towards assessing the reliability of a marine pilot practically.

5.2 Introduction

Previous studies have focused on factors influencing the operator's reliability in different disciplines independently, such as non-technical skills (Sharma et al., 2011; Flin et al., 2003), technical proficiency (Riahi et al., 2013; Alvarenga et al., 2014), and personal fatigue (Kim et al., 2009; Hetherington et al., 2006). This approach does not effectively mitigate human error, as evidenced by the continued existence of human failure leading to marine accidents (MAIB, 2016). Moreover, these studies have not identified the degree of interdependencies between factors as a single set, and they have not investigated the factors within marine port pilotage operations specifically; this points to a current research gap that needs to be filled. Therefore, this study investigates the factors highlighted in chapter 3 that challenge operator reliability during a pilotage operation as one set. This investigation is followed by development of novel MPRI that can enable decision makers to identify the risks to pilot performance associated with these factors.

In this research project, the researcher identified the primary qualitative contributing factors that expert pilots have highlighted as essential to their reliability during marine pilotage operations (see chapter 3). An investigation was conducted using different techniques (i.e., Delphi and AHP) and presented in chapter 4 to confirm the identified criteria highlighted throughout the interviews presented in former chapters and weight assignments. In this chapter, the researcher uses a systematic approach (see Figure 5.1), to identify the interdependencies among the identified MPRIs. Given the complexity of human interactions along with their subjective judgements in port activities and operations, developing effective MPRI will help decision makers to understand the interdependencies among the MPRIs and to select the appropriate measures to enhance the reliability of a marine pilot conducting an efficient pilotage operation. The presence of the subjective evaluations and feelings toward the identified criteria could have directly affected the evaluation process. Therefore, the researcher used a fuzzy decision making trial and evaluation laboratory (FDEMATEL) to identify the degree of interdependency among the identified factors constituting the MPRIs, followed by the use of analytical network process (ANP) to quantify and rank the criteria.

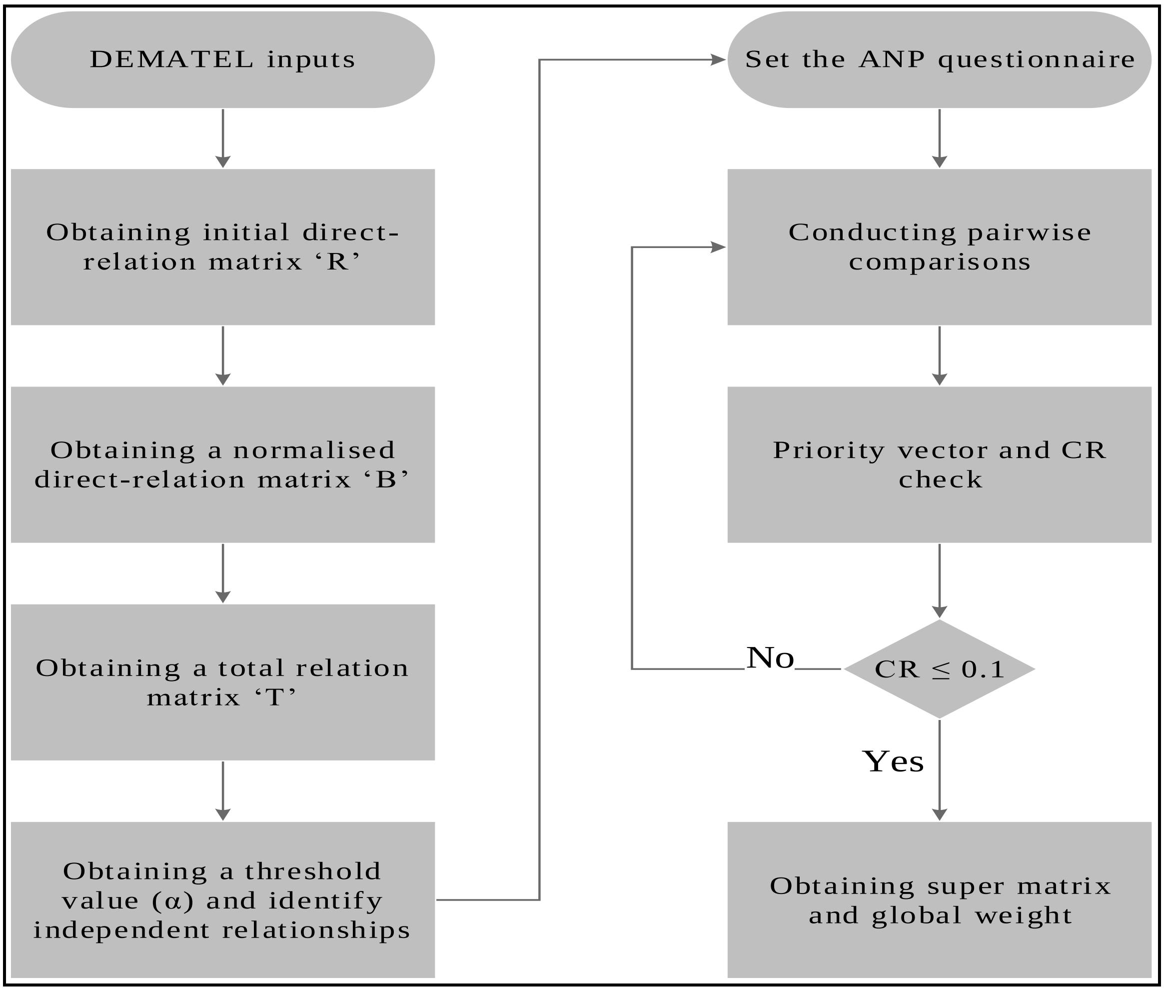

Figure 5.1. Research method framework

5.3 Research background

Solving such a complex operational issue, especially one that is intensively based on decision making and involves multiple players, necessitates development of a network that can explain how various factors influence other factors and what relations and interrelationships exist between factors (Saaty, 2001). Developing a network instead of a hierarchy helps decision makers to understand and identify the cause and effect relationship between criteria (Chen and Chen, 2010). The hierarchal model allows decision makers to examine the responses between factors (Ha and Yang, 2017). According to Saaty (2001), there are two forms of a hierarchal network: linear and non-linear (Figure 5.2). The non-linear network allows for identification and analysis of the interdependency between factors within a cluster and between clusters. Both the linear and non-linear network can be used to identify the interdependency between factors within a cluster (Saaty and Vargas, 2012). Interdependency can constitute outer dependence or inner dependence.

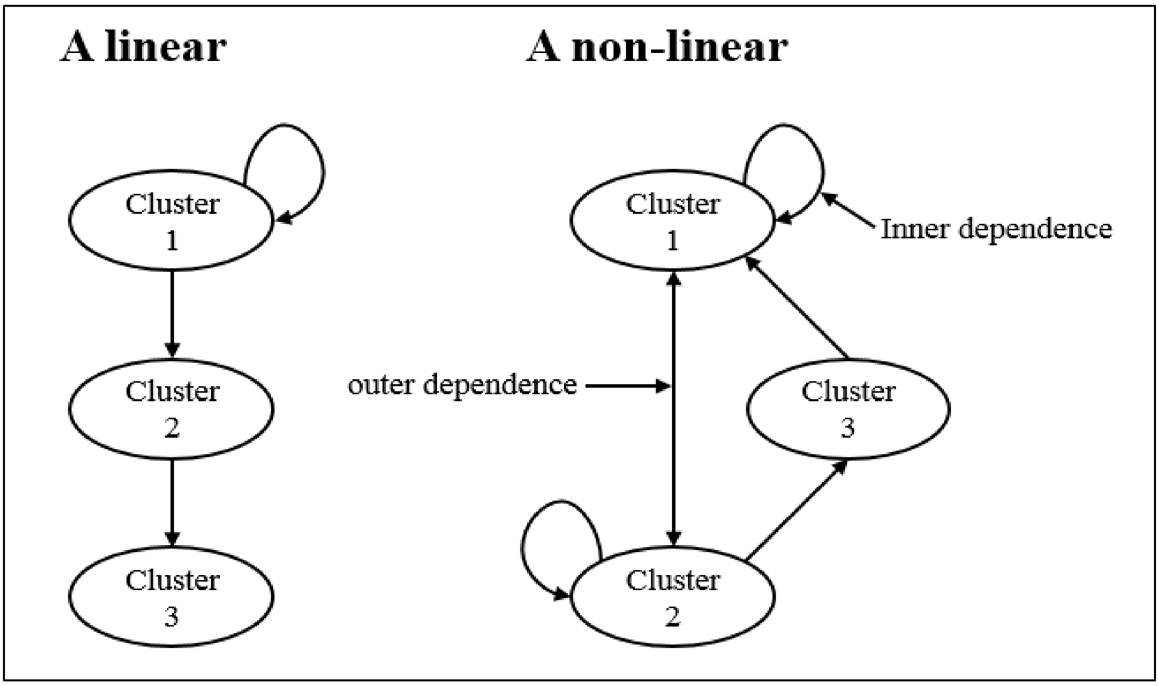

Figure 5.2. The differences between a hierarchy and a network structural model (Ha and Yang, 2017)

For this study, the author used a method with the ability to analyse and identify the interdependency between factors, as highlighted in Chapter 3. Structuring identified factors in a hierarchal model allows for a comprehensive understanding of the interactions among the complex operational and reliability shaping factors within an operation. This method is a hybrid approach that incorporates a FDEMATEL (Mohammadi et al., 2013) and ANP (Saaty, 1996). Although the ANP approach can identify the degree of interdependence between clusters and within clusters effectively, it was not feasible to use this approach independently for this study for the following two reasons:

1- It is costly and time consuming.
2- Experts will confuse pairwise comparisons of interdependencies.

The FDEMATEL method was used, due to ease of use, which makes it possible to determine if there were significant interdependencies among the criteria identified in previous chapters. Next, the ANP method was used based on factors that exceeded the threshold, resulting from the FDEMATEL application, which helped to quantify the intensity of the relationships among identified factors. This hybrid approach was used as it was difficult to quantify precise values when evaluating a complex system (Liou et al., 2007). The approach allowed the author to divide a complex system into subsystems to perform an effective measurement. It is worth mentioning that most critical situations involved in engineering practices when using an MCDM are subjected to quantitative and qualitative criteria with diverse types of uncertainties (Alyami et al., 2016). In most cases, qualitative criteria cannot be adequately assessed in a subjective form, since human judgments are inevitably associated with higher levels of uncertainties. This subjectivity manifests in the difficulties that humans face during assessments to provide complete judgements or when there is a lack of information, which is referred to as “ignorance” (incompleteness) (Alyami et al., 2016). Moreover, the vagueness on attribute meanings and their assessments were identified as the second factor, which is referred to as “fuzziness” (vagueness) (Guo et al., 2009).

5.4 MCDM methods in the literature

MCDM techniques have been widely recognised and used across disciplines. For instance, Boer et al. (2001) has suggested using MCDM methods in logistic investigations. Riahi et al. (2012) have also used MCDM techniques to assess the reliability of offshore seafarers. Chang et al. (2011) used one of the current MCDM techniques to develop supplier selection criteria. Liou and Tzeng (2012) addressed the importance of new MCDM methods and current trends. Zavadskas and Turskis (2011**)** illustrated and presented the main MCDM methods along with the primary steps. The primary steps of MCDM as seen in Opricovic and Tzeng (2004) are:

1- Establishing system evaluation criteria that relate system capabilities to goals;
2- Developing alternative systems for attaining the goals (generating alternatives);
3- Evaluating alternatives in terms of criteria (the value of the criterion functions);
4- Applying normative multi-criteria analysis methods;
5- Accepting one alternative as “optimal” (preferred);
6- If the final solution is not accepted, gather new information and go into the next iteration of multi-criteria optimisation.

The use of MCDM techniques has become more popular across different disciplines since it proves applicable in addressing different operational issues. For instance, Chen et al. (2011) and Ho et al. (2012) proposed a new Hybrid Dynamic Multiple Criteria Decision Making (HDMCDM) method for problem solving in interdependent and feedback-producing situations. Tzeng and Huang (2011) analysed the degrees of influence among criteria using an Influential Network Relation Map (INRM) that was generated and developed using a decision-making trial and evaluation laboratory (DEMATEL) technique in conjunction with ANP forming a DEMATEL-based Analytical Network Process (DANP). Chen and Yang (2011) applied fuzzy analytical network process FANP to evaluate firm risks under high uncertainty. Akyuz and Celik (2015) used a fuzzy decision-making trial and evaluation laboratory (FDMATEL) to evaluate critical operational hazards during a gas freeing operation in oil tankers. A new technique was employed by Yang et al. (2009) based on DEMATEL influential relation maps aimed to reduce the gap between aspiration level and performance: VIsekriterijumsko KOmpromisno Rangiranje (VIKOR). This technique was used in conjunction with a DEMATEL and DEMATEL-based Analytical Network Process (DANP) to assess and improve strategies; the technique was also used to streamline and improve strategies among dimensions and criteria to achieve desired levels (Chiu et al., 2013). This literature confirmed that the MCDM technique has shifted to assess and improve management performance compared to the traditional methods of ranking and selecting the most appropriate criteria (Opricovic and Tzeng, 2004).

In this study, the researcher used the DEMATEL MCDM technique in a fuzzy form along with the application of ANP. This approach was appropriate given the nature of the information available for achieving the main goal of this study. The integration of the DEMATL and ANP has been shown to be applicable for measuring dependency and obtaining feedback among criteria through application in several different fields (Liou et al., 2007; Shieh et al., 2010; Ha et al., 2017; Mohammadi et al., 2013; Alkhatib et al., 2015). This hybrid method was used to calculate the weight of each interdependent factor identified that affects the reliability of a marine pilot in a pilotage operation. This method can also be used with a mixed-method approach to weighing and identifying interdependencies, and it can be easily applied since it requires a relatively small number of participants for data analysis (Buyukozksn and Cifci, 2012).

The integration of the basic and the fuzzy form of DEMATEL and ANP, has been proven to be a successful tool for measuring dependency and feedback among elements in the complex decision problems in various applications.

Liou et al. (2007) investigated the safety of a Taiwanese airline using hybrid techniques of DEMATEL along with ANP through developing a new safety measurement model. The relationship between the cause and effect among the safety factors was identified and the safety measurement model was developed using the DEMATEL method. The researcher used the ANP to compare dependency and feedback among the identified criteria and their alternatives.

Other scholars have used AHP and DEAMTEL to identify factors that critically affect the performance in a supply chain industry (Najmi and Makui, 2010). AHP serves to value the relative weights of factors, while DEMATEL is used to investigate the interdependency among the factors.

In a study conducted by Alkhatib et al. (2015), researchers aimed to develop a method capable of evaluating and selecting the logistics service providers. This study was built based on the use of FDEMATEL and the Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS). The use of FDEMATEL was used to address the impact relationship among decision criteria, while the FTOPSIS was used to rank the selected logistic service provider based on their resources.

A Taiwanese study conducted by Wu and Tsai (2012) evaluated the criteria in the auto spare parts industry by combining the AHP and DEMATEL. The researchers used the AHP to highlight the critical criteria to address a short-term improvement strategy for supplier performance. The DEMATEL was used to suggest a long-term improvement opportunity for the industry.

A study conducted by Chiu et al. (2013) used a DEMATEL-based Analytical Network Process (DANP) and VIšekriterijumsko KOmpromisno Rangiranje (VIKOR) to assess and improve strategies that would ensure customer satisfaction when shopping from e-stores. This study aimed to provide knowledge to e-store managers to assess and improve strategies that influence customer satisfaction by interdependent and feedback problems among dimensions and criteria. Moreover, this study will help to reduce the performance gap among the dimensions and criteria to encourage customer purchases in the store.

Another study applied FDEMATEL to evaluate critical operational hazards in a crude oil tanker during the gas freeing process (Akyuz and Celik, 2015). This study identified and analysed the hazards that occurred during the gas freeing process with respect to cause and effect relationships. This study contributed to maritime safety at sea and environmental protection as well as to protection of human life on board seagoing tankers.

The use of FDEMATEL and ANP in a hybrid form has not yet been applied to evaluate the reliability of a human element in a marine pilotage operation in an interdependent situation. This study uses the integrated method for modelling MPRI interdependency for several reasons. First, the integrated method has been successfully applied in complex decision problems for group decision making. Second, it can illustrate the interdependencies among criteria in both quantitative and qualitative MPRIs, and add weights to the criteria. Third, this method requires a relatively small sample size for analysis.

For this study, the proposed methods were used in sequential form. The FDEMATEL was used first, followed by the use of ANP. The former was used to identify the interdependent relationship between the MPRIs, and the latter was used to determine the degree of relationship strength among the MPRIs. However, use of FDEMATEL to identify relations between the MPRIs is a novel application, and these relations have not been previously investigated in a holistic form within marine port pilotage operations. More importantly, the identified factors have been identified and investigated by different scholars in more independent forms (i.e. Alvarenga et al., 2014; Yule and Brown, 2012; Hetherington et al., 2006). However, through this study, factors highlighted by experts as significant in shaping the reliability were used in holistic forms, as can be seen in chapter 4. This study aims to highlight the degree of interdependency between these factors in shaping an operator’s reliability in order to develop an effective set of MPRIs using the proposed hybrid method.

The FDEMATEL method was used first to identify if there were any significant interdependencies among the criteria identified in previous chapters. Next, the ANP method was used to help quantify the intensity of the relationships among the identified factors.

5.4.1 The use of FDEMATEL for MPRIs interdependency identification

The DEMATEL method was invented by the Science and Human Affairs Program of the Battelle Memorial Institute in Geneva Research Centre around the mid-1970s. The objective behind the invention of DEMATEL was to investigate and solve social complexity and intertwined problems (Wu et al., 2010). This method has a structural approach that distinguishes between cause and effect, and builds an influential network relation map (INRM) (Chiu et al., 2013) According to Liou et al. (2007), a diagraph makes it possible to demonstrate the direct relationships and interdependency among the criteria. The diagraph can help predict the behaviour of the firm when taking into account the interdependency among the criteria (Lee and Lin, 2013). The DEMATEL method was modified to a fuzzy form due to the multiplicity of the criteria that the MCDM's methods used; the alternatives were then judged either qualitatively or quantitatively by the decision makers (Dalalah et al., 2011). This form of assessment was used to identify the value of each alternative with respect to the overall objective of the problem. This assessment was also used to make the complex and challenging process of the operational decision making much easier. However, the assessment resulted in uncertain, imprecise, indefinite, and subjective data, which confused decision makers and forced them to decide in a fuzzy environment. To model the uncertainty and imprecise data, the fuzzy sets theory is an efficient method to employ (Alyami et al., 2014). Fuzzy sets provide essential flexibility for decision makers to manage the uncertainty and imprecision caused by lack of knowledge or ill-defined information (Chang et al., 2011). This method was invented by Zadeh in 1965 and used to describe the linguistic information across different disciplines.

Moreover, this method has proved its capability to represent gradual changes in people's recognition of a concept unlike when using conventional evaluations such as True/False, High/Low, Yes/No, etc. (Alyami et al., 2014; Dalalah et al., 2011; Zadeh, 1975).

Lin and Wu (2008) developed a fuzzy DEMATEL to apply to matrices and graphs for viewing the structure of complex causal relationships. This method incorporates group decision making that aims to gather ideas to analyse the cause and effect relationship that occurs in complex issues. Therefore, to cope with the fuzzy data in this study, the researcher used linguistic evaluations in order to rate the identified criteria within the proposed MPRIs. To manage the vagueness in the evaluation, fuzzy logic and triangular fuzzy sets were proposed as per Dalalah et al. (2011). A fuzzy subset A can be defined by a membership function $\mu_A(x)$, which maps each element x in X to a real number in the interval [0,1] (Alkhatib et al., 2015). A fuzzy number 'A' can be defined as a triangular fuzzy number if its membership function is $0 < l \leq m \leq u \leq \infty$ (Ding and Liang, 2005; Akyuz and Celik, 2015).

$$\mu_A(x) = \begin{cases} 0, & x < l \\ (x-l)/(m-l), & l \leq x \leq m, \\ (u-x)/(u-m), & m \leq x \leq u, \\ 0, & x \geq u \end{cases} \tag{5.1}$$

Where $l, m,$ and u represent crisp values. A triangular fuzzy number can be denoted by (l, m, u), lower, medium and upper numbers of the fuzzy sets $(x \leq y \leq z)$. In light of the above, a triangular fuzzy number is shown in Figure 5.3.

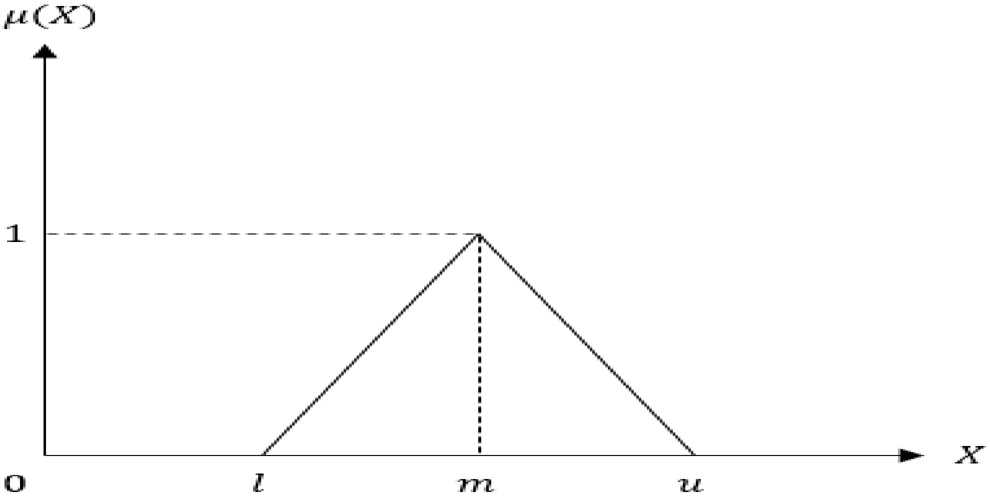

Figure 5.3. Triangular fuzzy number

The distance between fuzzy numbers can be calculated using different approaches (Heilpern, 1997; Fu, 2008). In this study, the researcher calculated the distance for a pair of triangular fuzzy numbers (TFN), $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$ with the following equation (Dalalah et al., 2011):

$$d(\tilde{a}, \tilde{b}) = \left|\tilde{a}^{def} - \tilde{b}^{def}\right|, \tag{5.2}$$

Where $\tilde{a}^{def}$and $\tilde{b}^{def}$are the defuzzification points of $\tilde{a}$ and $\tilde{b}$. For any fuzzy number, the defuzzification point can be obtained by calculating the point that divides the area of the fuzzy set into two equal parts. Accordingly, the defuzzification point can be given by the following equation (Alkhatib et al., 2015):

$$defuzz.point = \begin{cases} u - \sqrt{(u-l)(u-m)/2}, & u - m > m - l \\ \sqrt{(u-l)(u-m)/2} - l, & u - m < m - l \\ m, & u - m = m - l \end{cases} \tag{5.3}$$

It should be noted that this calculated distance satisfies the following properties: first, $d(\tilde{a}, \tilde{a})$= 0; second, $d(\tilde{a}, \tilde{b})$= $d(\tilde{b}, \tilde{a})$; and the last property, the TFN $\tilde{b}$ is closer to $\tilde{a}$ than to $\tilde{c}$ if and only if $d(\tilde{a},\tilde{b}) < d(\tilde{a},\tilde{c})$ (Dalalah et al., 2011). If the distance is equal to zero between two fuzzy sets, then a similarity measure of 1 will result. However, the farther the distance the lower similarity obtained.

It is worth mentioning that the use of the TFN membership function and its associated parameters helps to reflect the fuzziness of the evaluation data, where the narrower the interval $[l,u]$, the lower the fuzziness of the evaluation data.

The FDEMATEL application consists out of four main steps (Alkhatib et al., 2015) starting with identifying the initial direct-relation matrix, obtaining normalised direct-relation matrix, obtaining a total-relation matrix and obtaining a threshold value for constructing the diagraph. Therefore, the relation among the MPRIs can be calculated using FDEMATEL approach as follows:

Step 1: Obtain the average matrix of an initial direct-relation matrix R.

The initial direct-relation matrix (R) is an average $n \times n$ matrix constructed by pairwise comparison in terms of directions and strength of influences between MPRIs. The pairwise comparison scale for this study ranged from 0 to 4: 0 (No influence), 1 (Very low influence), 2 (Low influence), 3 (High influence), and 4 (Very high influence). This is the standard as proposed by the DEMATEL method seen in Ha et al. (2017). However, as aforementioned, a fuzzy DEMATEL was proposed in this study. Accordingly, the value of a fuzzy form to each comparison scale is represented in Table 5.1.

Table 5.1. Influence measures using linguistic terms

Rating scale	Linguistic terms	Linguistic values
0	No influence (No)	(0,0,0.25)
1	Very low influence (VL)	(0,0.25,0.5)
2	Low influence (L)	(0.25,0.5,0.75)
3	High influence (H)	(0.5,0.75,1.0)
4	Very high influence (VH)	(0.75,1.0,1.0)

In this research, defuzzyfication processes were applied using equation 5.3 at the beginning when obtaining the initial-direct relation matrix, as seen in Ha et al. (2017). As shown in equation 5.4, the initial direct-relation matrix $R = [r_{ij}]_{n\times n}$, where r_{ij} is an average directed-relation value if $x_{ij}$and all principal diagonal $r_{ij}(i = j)$ are equal to zero, $X^k = [x_{ij}^k]$ is an expert judgement on the causal relationship of x_{ij} by the kth expert.

$$R = [r_{ij}]_{n\times n} = \frac{1}{m}\sum_{k=1}^{m} x_{ij}^k, \qquad i,j = 1 \dots \dots . n \tag{5.4}$$

The fuzzy initial direct-relation matrix can be built as

$$\tilde{R} = \begin{bmatrix} \tilde{r}_{11} & \cdots & \tilde{r}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{r}_{n1} & \cdots & \tilde{r}_{nn} \end{bmatrix}$$

Where each $\tilde{r}_{ij}$= (l_{ij}, m_{ij}, u_{ij}) is a TFN and $\tilde{r}_{ij}$(i-1,2,…, n) is the average of experts' evaluations of the $i^{th}$and j^{th} factors impact-relation and regarded as a TFN (0,0,0) since all principal diagonal $\tilde{r}_{ij}(i = j)$ are equal to zero.

<u>Step 2: Calculate a normalised direct-relation matrix B.</u>

The normalised direct-relation matrix$B = [b_{ij}]_{n\times n}$, where the value of each MPRI in matrix B is $0 \leq b_{ij} \leq 1$, can be obtained through following equation 5.5.

$$\tilde{B} = \begin{bmatrix} \tilde{b}_{11} & \cdots & \tilde{b}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{b}_{n1} & \cdots & \tilde{b}_{nn} \end{bmatrix} \tag{5.5}$$

Where

$$\tilde{b}_{ij} = \frac{\widetilde{r_{ij}}}{s}, \text{ and } s = max_{l\leq i\leq n}(\textstyle\sum_{j=1}^{n} r_{ij})$$

<u>Step 3</u>**<u>: Obtain a total-relation matrix T.</u>***

By using equation 5.6, the total-relation matrix T can be obtained via normalising the matrix B, which represents the direct-relation matrix explained above.

$$T = \lim_{m=\infty}(B^1 + B^2 + \cdots + B^m) = \sum_{m=1}^{\infty} B^i = B(I-B)^{-1} \qquad (5.6)$$

Where I is representing the identity matrix.

The fuzzy total-relation matrix can be obtained using the formula presented by Lin and Wu (2008):

$$\tilde{T} = \lim_{m=\infty}(B^1 + B^2 + \cdots + B^m)$$

$$\tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \cdots & \tilde{t}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \cdots & \tilde{t}_{nn} \end{bmatrix}$$

Where $\tilde{t}_{ij}$is TFN, and the $\tilde{T}$matrix is developed based on

$$\tilde{T} = B(I-B)^{-1}$$

Where I is the fuzzy identity matrix (Hosseini and Tarohk, 2013).

Following the development of matrix $\tilde{T}$, the sum of the rows (R_i) and the sum of columns (C_j), in which (t_{ij}) indicates the interdependent value of each pair of the investigated MPRIs. Since $r_i + c_i$is shows all effects that are given and received by criterion i. Therefore, $r_i + c_j$shows both criterion i's impact on the entire system and other system factors impact upon factor i. Thus, the indicator $r_i + c_j$can present the degree of importance of criterion i with respect to the total system. On the contrary, the difference of the two, $r_i - c_j$, represents the net effect that the criterion i has on the system. Precisely, if $r_i - c_j$ results in a positive value, then the factor i will be a net cause. On the other hand, if $r_i - c_j$ shows a negative value, then the factor will be an effect group (Yang et al., 2008; Akyuz and Celik, 2015).

Eq. 5.7 shows how to classify the cause and effect values.

$$R_i = \sum_{j=1}^{n} t_{ij}, C_j = \sum_{i=1}^{n} t_{ij} (i,j = 1,2, \ldots . s \ldots , n)$$

$$pr_i^{+} = R_i + C_{i,}\ pr_i^{-} = R_i - C_i \tag{5.7}$$

<u>Step 4</u>: *<u>Obtain a threshold value (α) and construct a diagraph.</u>*

Determining the value of the threshold can be obtained subjectively, with an expert's judgement, or mathematically (Liou et al., 2007; Shieh et al., 2010; Ha et al., 2017). The significance of setting a threshold value (α) is that it is used to eliminate the factors that have less influence on others in the total-relation matrix (T). In this study, the value of the threshold was determined by the average value of (t_{ij}) using equation 5.8.

$$\alpha = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij}}{N} \tag{5.8}$$

Where N represents the total number of elements ($i \times j$)

When the identified value of the MPRI whose influence on the values of (t_{ij}) is more than the identified threshold, these MPRIs can be selected and converted into a causal relationship diagram (Ha et al., 2017).

5.4.2 The use of ANP to determine the interdependency weights between MPRIs

The use of DEMATEL helps to identify the interdependent relationships between factors that constitute the MPRIs. However, the essential part of using the ANP method is to obtain the final adjusted weight of the entire identified interrelated criterion. According to Saaty (1996), the ANP was developed on the basis of the analytical hierarchy process (AHP) to elucidate the dependence and feedback among the criteria and alternatives. As aforementioned, the AHP allows interaction and feedback within the cluster. Unlike the AHP, the ANP allows the interaction within and between clusters (Saaty, 2001). The initial step of the ANP method is comparing the criteria in the entire system to form a super matrix through pairwise comparison. The common question when asking the expert to compare is “how much importance does criterion ‘a’ influence criterion ‘b’?” (Ha et al., 2017). Similar to the AHP method, the ANP utilises the scale ranging from 1 (equal importance) to 9 (extreme importance) (Huang et al., 2005). Accordingly, the unweighted super matrix consists of the local weights identified by the pairwise comparisons, thus forming the super matrix shown in equation 5.9.

$$W = \begin{array}{ccc} & & \begin{array}{cccc} C_1 & C_2 & \cdots & C_N \\ e_{11}e_{12}\ldots e_{1n_1} & e_{21}e_{22}\ldots e_{2n_2} & & e_{N1}e_{N2}\ldots e_{Nn_N} \end{array} \\ \begin{array}{c} C_1 \\ \\ \\ \\ C_2 \\ \\ \\ \vdots \\ \\ \\ C_N \\ \\ \\ \end{array} & \begin{array}{c} e_{11} \\ e_{12} \\ \vdots \\ \vdots \\ e_{1n_1} \\ e_{21} \\ e_{22} \\ \vdots \\ e_{2n_2} \\ e_{m1} \\ e_{m2} \\ \vdots \\ e_{mn_m} \end{array} & \begin{bmatrix} W_{11} & W_{12} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \vdots & \vdots & \cdots & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix} \end{array} \qquad (5.9)$$

The ANP is a non-linear network where the unweighted super matrix of this network can be expressed by the matrix seen in Ha et al. (2017):

$$W = \begin{bmatrix} 0 & W_{12} & 0 \\ 0 & W_{22} & W_{23} \\ W_{31} & 0 & W_{33} \end{bmatrix}$$

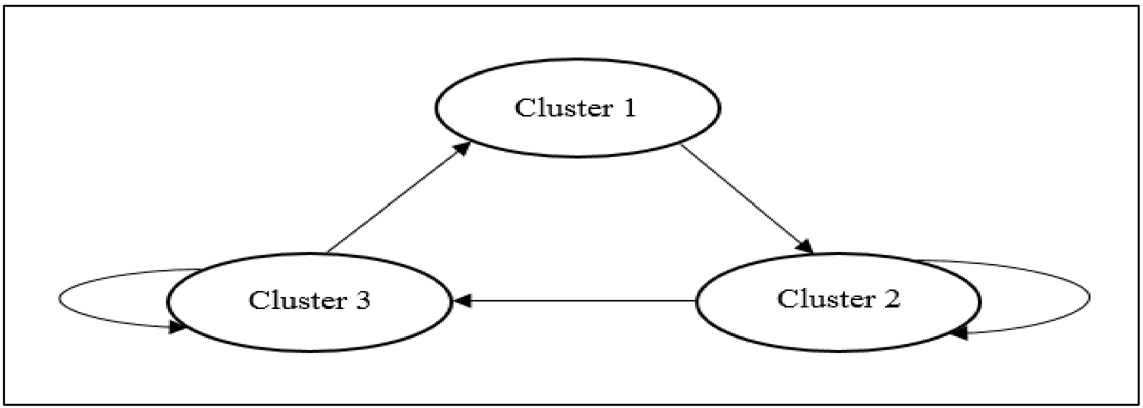

Figure 5.4. Illustration of system structure

Where W_{12} is a matrix that represents the weight of cluster 1 with respect to cluster 2, W_{23}represents the weight of cluster 2 with respect to cluster 3. In addition, W_{31} represents the weight of cluster 3 with respect to cluster 1. Finally the W_{22} and W_{33} are indicated as the inner dependence and feedbacks within clusters 2 and 3, respectively. It is important to highlight that the unweighted super matrix (W_{NN}) includes their associated elements' unweighted super matrix (Ha and Yang, 2017), where the (i, j) block of the matrix (W_{NN}) is given by

$$W_{ij} = \begin{bmatrix} w_{i1}^{(j1)} & w_{i1}^{(j2)} & \dots & w_{i1}^{(jn_j)} \\ w_{i2}^{(j1)} & w_{i2}^{(j2)} & \dots & w_{i2}^{(jn_j)} \\ \dots & \dots & \dots & \dots \\ w_{in_i}^{(j1)} & w_{in_i}^{(j2)} & \dots & w_{in_i}^{(jn_j)} \end{bmatrix}$$

A weighted super matrix (w_{ANP}) can be developed by multiplying the partitioned matrix $(B = W_{ij})$ in the unweighted super matrix by the associated cluster weights w_i using equation 5.10 (Saaty, 2001).

$$w_{ANP} = Bw_i \qquad (5.10)$$

Where B represents the partitioned matrix in the unweighted super matrix and w_i denotes the weights for their associated cluster weights.

The matrices (B) and (w_{ij}) were developed based on the pairwise comparisons conducted based on the diagraph of DEMATEL (Ha and Yang, 2017). Moreover, these pairwise comparisons are conducted using the nine-point scale developed by Saaty in 1980's, which forms a number of comparison matrices that help to identify the relative impacts of the MPRIs' interdependency. The weights are then derived from these comparisons and entered as the elements of columns of the matrix (B). Then, a weighted super matrix can be normalised by setting all columns sum to unity. The sum of the probabilities of all states is set equal to one. Finally, the limit super matrix can be obtained by raising the weighted super matrix to limiting powers using $W^{\infty} = \lim_{k \to \infty} W^{k}$ until the column numbers are the same in every column. The values in the column represent the global weights of the associated MPRIs.

5.5 A case study to identify MPRIs' interdependency and evaluate their weights using FDEMATEL and ANP

5.5.1 FDEMATEL

Several senior pilots were asked to participate in the study to determine the interdependencies among the four main dimensions and the 13 sub-criteria by providing their opinions in a questionnaire. The questionnaire was used to ascertain expert opinions on the selected methodology. Similar to the study done by Buyukozksn and Cifci (2012), this method required a relatively small number of participants to collect data for analysis. Accordingly, five senior marine port pilots with significant work experience were contacted by email, to complete the questionnaire. The demographic details of those participating pilots are shown in Table 5.2.

Table 5.2. Experts' demographic

Expert	Gender	Age Group	Rank	Qualification	Working Experience
1	Male	30-39	Senior Pilot	Master + PL	6 – 10 Years
2	Male	40-49	Senior Pilot	Second Officer + PL	>20 years
3	Male	40-49	Senior Pilot	Master + PL	>20 years
4	Male	50-59	Senior Pilot	Diploma + PL	>20 years
5	Male	50-59	Senior Pilot	Diploma + PL	>20 years

The four main dimensions that shape MPRIs were identified in previous chapters of this study. However, this chapter aims to re-test and identify the main contributing factors that are essential in shaping a marine pilot's reliability. Moreover, this chapter aims to identify the degree of interdependency among factors and assigning weights. The four main dimensions are operator technical proficiency (TP), personal fatigue (PF), non-technical skills (NTS), and fitness and strength (F&S). As a higher level of uncertainty was present when experts expressed their opinions, the marine pilots were asked to evaluate, based on their opinions, the extent to which they believe that factor 'i' influenced factor 'j' using the linguistic terms used for a triangular membership function (see Table 5.1).

First step: Developing the initial direct-relation matrix (R) for main dimensions

The average constructed fuzzy initial-directed matrix '$\grave{R}$' was obtained using Eq. 5.4. The same process was used on each dimension and sub-dimension to obtain the $\grave{R}$ 4 × 4 and 13 × 13 matrix R forming the main dimensions and sub-criteria, respectively. A demonstration process was thereby developed for the matrices wherein the full response from the experts based on the four main dimensions was given as shown in Table 5.3. This table shows the degree of influence that experts perceive exists between the four main dimensions.

Table 5.3. Experts' evaluations of the four main dimensions on MPRI

Expert	**TP-PF**	**TP-NTS**	**TP-F&S**	**PF-TP**	**PF-NTS**	**PF-F&S**	**NTS-TP**	**NTS-PF**	**NTS-F&S**	**F&S-TP**	**F&S-PF**	**F&S-NTS**
1	L	VH	NO	L	H	VH	VL	VL	VL	H	VH	H
2	L	H	NO	H	H	VH	L	L	NO	L	H	VH
3	H	VH	VL	H	VH	VH	VL	H	L	L	VH	VH
4	L	VH	L	L	VH	VH	L	L	L	H	VH	H
5	L	H	VL	L	VH	VH	NO	H	NO	L	VH	VH

(**TP**: Technical Proficiency; **PF**: Personal Fatigue; **NTS**: Non-Technical Skills; **F&S**: Fitness & Strength), (**No**: No influence; **VL**: Very Low; **L**: Low; **H**: High; **VH**: Very High)

Accordingly, an aggregated $\grave{R}$ matrix can be developed by taking the average of each comparison to form the initial fuzzy direct-relation matrix ($\grave{R}$) as shown in Table 5.4.

Table 5.4. Initial fuzzy direct-relation matrix ($\grave{R}$) for MPRIs' main dimensions

$\grave{R}$ matrix	**TP**	**PF**	**NTS**	**F&S**
TP	(0,0,0)	(0.30,0.55,0.80)	(0.65,0.90,1.00)	(0.05,0.20,0.45)
PF	(0.35,0.60,0.85)	(0,0,0)	(0.65,0.90,1.00)	(0.75,1.00,1.00)
NTS	(0.10,0.30,0.55)	(0.30,0.55,0.80)	(0,0,0)	(0.10,0.25,0.50)
F&S	(0.35,0.60,0.85)	(0.70,0.95,1.00)	(0.65,0.90,1.00)	(0,0,0)

(**TP**: Technical Proficiency; **PF**: Personal Fatigue; **NTS**: Non-Technical Skills; **F&S**: Fitness & Strength)

The researcher defuzzified the $\grave{R}$ matrix and formed the defuzzified initial direct-relation matrix (R) as seen in Table 5.5 by using equation 5.3.

Table 5.5. Initial defuzzified direct-relation (R) matrix for MPRIs' main dimensions

***R* matrix**	**TP**	**PF**	**NTS**	**F&S**
TP	0	0.55	0.78	0.23
PF	0.60	0	0.78	0.75
NTS	0.31	0.55	0	0.28
F&S	0.60	0.79	0.78	0

(**TP**: Technical Proficiency; **PF**: Personal Fatigue; **NTS**: Non-Technical Skills; **F&S**: Fitness & Strength)

Second step: Developing a normalised direct-relation matrix (B) for main dimensions

The second step of the DEMATEL technique is to normalise the initial direct-relation matrix (B) (Table 5.5) using equation 5.5 as shown in Table 5.6. This can be achieved by dividing each $r_{ij}$from the R matrix by the maximum sum of column and rows in the matrix R. The maximum sum was obtained and equalled 2.3469. Subsequently, matrix B values are shown in Table 5.6:

Table 5.6. Normalised direct-relation matrix (B) for MPRIs' main dimensions

B **matrix**	**TP**	**PF**	**NTS**	**F&S**
TP	0	0.23	0.33	0.10
PF	0.26	0	0.33	0.32
NTS	0.13	0.23	0	0.12
F&S	0.26	0.34	0.33	0

(**TP**: Technical Proficiency; **PF**: Personal Fatigue; **NTS**: Non-Technical Skills; **F&S**: Fitness & Strength)

Third step: obtaining total relation matrix (T) for main dimensions

The normalised direct-relation matrix (B) helps transform the scale of differing criteria into a comparable form; the process completes the third step of the DEMATEL method. The third step of the method aims to identify the total relation matrix (T) using equation 5.6 as shown in Table 5.7.

Table 5.7. Total relation matrix (T) for MPRIs' main dimensions

T **matrix**	**TP**	**PF**	**NTS**	**F&S**
TP	0.40	**0.68**	**0.84**	0.45
PF	**0.75**	0.67	**1.05**	**0.73**
NTS	0.45	0.59	0.48	0.41
F&S	**0.76**	**0.93**	**1.06**	0.50

(**TP**: Technical Proficiency; **PF**: Personal Fatigue; **NTS**: Non-Technical Skills; **F&S**: Fitness & Strength)

Table 5.7 summarises the influence ratings that the experts expressed in the questionnaire regarding the four main dimensions that shape MPRIs. Each figure within this matrix represents the total direct and indirect influence of each dimension 'i' over dimension 'j'. For instance, the total direct and indirect influence of the TP over PF is (0.68). The sum of the TP row (R_i) (2.3705) represents the total direct and indirect influence that the TP has over an operator's reliability. In contrast, the total sum of the TP column (C_i) (2.3662) represents the total direct and indirect influence of the operator's reliability over the TP dimension, as shown in Table 5.8.

Table 5.8. Direct, indirect relations and type of MPRIs main dimensions

MPRI's	R_i	C_i	$R_i + C_i$	$R_i - C_i$	Type
TP	2.3705	2.3662	4.7367	0.0043	Cause
PF	3.1961	2.8613	6.0573	0.3348	Cause
NTS	1.9327	3.4362	5.3689	-1.5036	Effect
F&S	3.2457	2.0812	5.3268	1.1645	Cause

(**TP**: Technical Proficiency; **PF**: Personal Fatigue; **NTS**: Non-Technical Skills; **F&S**: Fitness & Strength)

Out of the T matrix, only factors with effect greater than the average value, which called

Fourth step: obtaining threshold out of the total relation matrix (T) for main dimensions

Out of the T matrix, only factors with an effect greater than the average value, called 'Threshold' (Tzeng et al., 2007; Shieh et al., 2010; Alkhatib et al., 2015), of the matrix were chosen and in turn shown in the visual diagram of the relation and influence matrix. The threshold indicates the interdependent relationships between the relevant factors. Identifying the threshold value is the fourth step of the DEMATEL method. In this case study, the threshold value of the four main dimensions in the T matrix is (0.6716). Accordingly, only the shaded cells in Table 5.7 were represented in the influence and relation diagram, Figure 5.5.

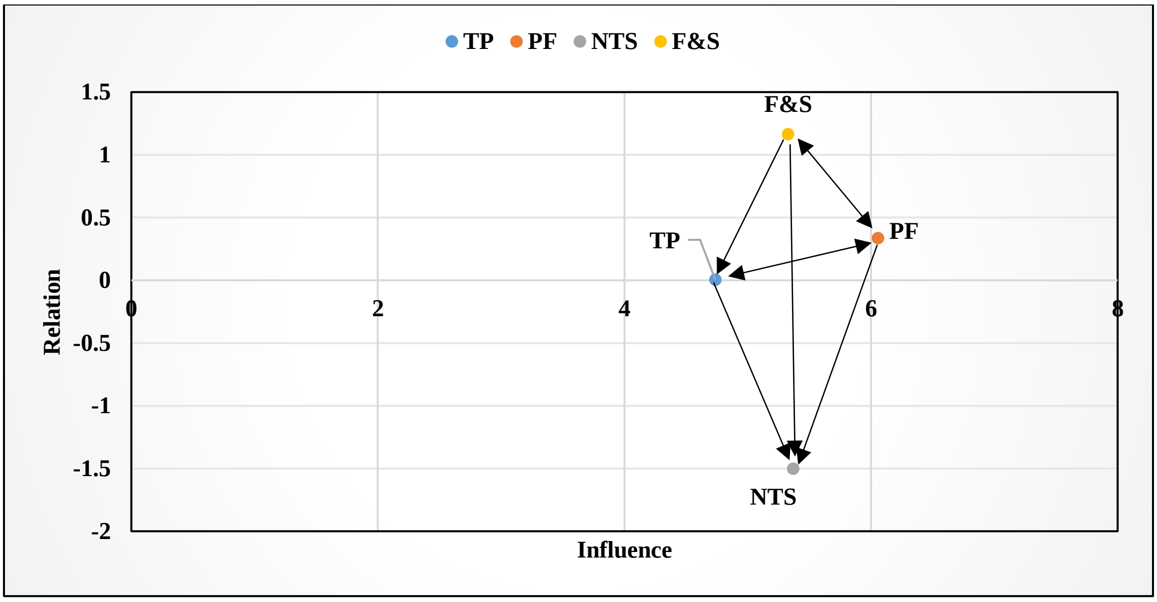

Figure 5.5. MPRIs main dimensions relation and influence diagram

In the diagram, the horizontal axis ($\boldsymbol{R_i} + \boldsymbol{C_i}$) provides an index representing the total effects both given and received by factor 'i', which shows the degree of importance that factor 'i' plays within the model. On the other hand, the vertical axis ($\boldsymbol{R_i} - \boldsymbol{C_i}$), represents the net effect that factor 'i' contributes to the model. When ($\boldsymbol{R_i} - \boldsymbol{C_i}$) showing a negative relation, this means that factor 'i' is a net receiver and belongs to the effect group (Dalalah et al., 2011; Tzeng et al., 2007; Tamura et al., 2002), such as NTS. Nonetheless, if ($\boldsymbol{R_i} - \boldsymbol{C_i}$) is positive, this means that factor 'i' is a net causer and belongs to the cause group such as TP, PF and F&S.

Similar to the above process, the initial direct-relation matrix 'R', the normalised relation matrix 'B', the total relation matrix 'T', and the cause and effect relationships table, including all of the identified dimensions and associated criteria, and using an identified threshold value of 0.0791 for the 13 sub-criteria, were summarised in Tables 5.9–5.12. In addition, only the shaded cells in Table 5.11 were represented in the influence and relation diagram, Figure 5.6.

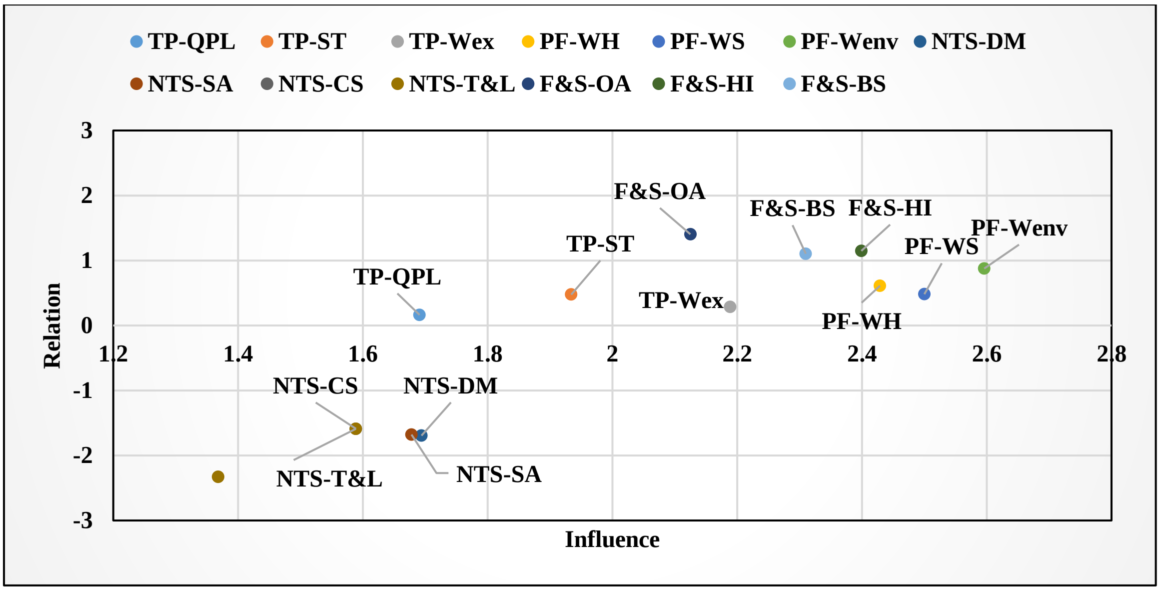

Figure 5.6. MPRIs main dimensions relation and influence diagram

Among the 13 identified MPRIs, the highest influential factors shown in Table 5.12 are personal fatigue, work environment, work stresses, and work hours. These were followed by operator HI, BS and WEx. To work towards maintaining higher operators' reliability, the decision makers must consider placing higher standards on these factors, since these factors can degrade the reliability of a marine pilot when conducting pilotage services. The least influential factors were SA , CS, T&L. For instance, WEnv is one of the factors that cause fatigue in a marine pilot, but it can be diminished by other factors including, but not limited to, relationships with co-workers, management strategies, and the weather. Therefore, work environment has an effect on the pilot's ability to obtain new qualifications and to attend ST about management strategies, and therefore, WEnv affects the pilot's experience level. Moreover, poor relationships with co-workers or bad weather can affect a marine pilot's DM. Namely, high-level CS are needed to convey essential operational information to a team and thereby to build proper operational images and make the required decision. Since lower-level WEnvs' have an influence on PF, the results also show that WEnv has an effect on the health and BS of the pilot. WEnv is also influenced by the criteria of TP and NTS clusters as well as by HI and BS. For instance, T&L influence the WEnv in such a way that if the pilot is not capable of managing team members as a leader and defusing conflict among team members, then the WEnv is likely to carry high tension, and therefore the pilot will become fatigued under the influence of stress.

The interdependencies among the criteria can be seen from the examples elaborated in the previous paragraph, as well as illustrated by the shaded cells in Table 5.11. However, the degree of interdependencies and how much these factors are influenced and affected by each other can be obtained using the method of ANP.

Table 5.9. Initial direct-relation matrix (R) for 13 sub-criterion of MPRIs’

***R* MPRIs**		**TP**			**PF**			**NTS**				**F&S**		
		QPL	**ST**	**WEx**	**WH**	**WS**	**WEnv**	**DM**	**SA**	**CS**	**T&L**	**OA**	**HI**	**BS**
TP	**QPL**	0.00	0.00	0.00	0.30	0.55	0.60	0.77	0.72	0.65	0.77	0.00	0.00	0.00
	ST	0.00	0.00	0.00	0.77	0.72	0.70	0.75	0.78	0.78	0.71	0.00	0.00	0.00
	WEx	0.00	0.00	0.00	0.76	0.77	0.71	0.79	0.79	0.78	0.78	0.00	0.00	0.00
PF	**WH**	0.23	0.18	0.77	0.00	0.00	0.00	0.77	0.79	0.66	0.60	0.55	0.77	0.71
	WS	0.23	0.23	0.55	0.00	0.00	0.00	0.75	0.75	0.79	0.79	0.45	0.79	0.77
	WEnv	0.66	0.71	0.60	0.00	0.00	0.00	0.79	0.75	0.79	0.79	0.35	0.78	0.77
NTS	**DM**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	SA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	T&L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F&S	**OA**	0.66	0.71	0.79	0.78	0.79	0.45	0.78	0.79	0.67	0.72	0.00	0.00	0.00
	HI	0.76	0.70	0.70	0.66	0.75	0.60	0.79	0.75	0.77	0.73	0.00	0.00	0.00
	BS	0.78	0.65	0.60	0.66	0.79	0.60	0.77	0.78	0.60	0.61	0.00	0.00	0.00

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength)).

Table 5.10. Normalised direct-relation matrix (B) for the 13 sub-criteria of MPRIs

***B* MPRIs**		**TP**			**PF**			**NTS**				**F&S**		
		QPL	**ST**	**WEx**	**WH**	**WS**	**WEnv**	**DM**	**SA**	**CS**	**T&L**	**OA**	**HI**	**BS**
TP	**QPL**	0.00	0.00	0.00	0.04	0.08	0.08	0.11	0.10	0.09	0.11	0.00	0.00	0.00
	ST	0.00	0.00	0.00	0.11	0.10	0.10	0.10	0.11	0.11	0.10	0.00	0.00	0.00
	WEx	0.00	0.00	0.00	0.11	0.11	0.10	0.11	0.11	0.11	0.11	0.00	0.00	0.00
PF	**WH**	0.03	0.02	0.11	0.00	0.00	0.00	0.11	0.11	0.09	0.08	0.08	0.11	0.10
	WS	0.03	0.03	0.08	0.00	0.00	0.00	0.10	0.10	0.11	0.11	0.06	0.11	0.11
	WEnv	0.09	0.10	0.08	0.00	0.00	0.00	0.11	0.10	0.11	0.11	0.05	0.11	0.11
NTS	**DM**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	SA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	T&L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F&S	**OA**	0.09	0.10	0.11	0.11	0.11	0.06	0.11	0.11	0.09	0.10	0.00	0.00	0.00
	HI	0.11	0.10	0.10	0.09	0.10	0.08	0.11	0.10	0.11	0.10	0.00	0.00	0.00
	BS	0.11	0.09	0.08	0.09	0.11	0.08	0.11	0.11	0.08	0.08	0.00	0.00	0.00

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength)).

Table 5.11. Total relation matrix (T) for the 13 sub-criteria of MPRIs

T MPRIs		TP			PF			NTS				F&S			R_i
		QPL	**ST**	**WEx**	**WH**	**WS**	**WEnv**	**DM**	**SA**	**CS**	**T&L**	**OA**	**HI**	**BS**	
TP	**QPL**	0.02	0.02	0.03	0.05	**0.09**	**0.09**	**0.15**	**0.14**	**0.13**	**0.14**	0.01	0.03	0.02	0.93
	ST	0.03	0.03	0.04	**0.13**	**0.12**	**0.11**	**0.16**	**0.17**	**0.16**	**0.15**	0.02	0.04	0.04	1.20
	WEx	0.03	0.03	0.04	**0.12**	**0.13**	**0.12**	**0.17**	**0.17**	**0.17**	**0.17**	0.02	0.04	0.04	1.24
PF	**WH**	0.07	0.06	**0.15**	0.06	0.06	0.05	**0.19**	**0.19**	**0.17**	**0.16**	**0.09**	**0.13**	**0.12**	1.52
	WS	0.07	0.07	**0.12**	0.05	0.06	0.05	**0.18**	**0.18**	**0.18**	**0.18**	0.07	**0.13**	**0.12**	1.49
	WEnv	**0.14**	**0.14**	**0.13**	0.06	0.07	0.06	**0.21**	**0.20**	**0.20**	**0.20**	0.06	**0.13**	**0.13**	1.74
NTS	**DM**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	SA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	T&L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F&S	**OA**	**0.12**	**0.13**	**0.16**	**0.16**	**0.16**	**0.11**	**0.21**	**0.21**	**0.19**	**0.20**	0.03	0.05	0.04	1.76
	HI	**0.14**	**0.13**	**0.15**	**0.14**	**0.16**	**0.13**	**0.21**	**0.20**	**0.20**	**0.20**	0.03	0.05	0.04	1.77
	BS	**0.14**	**0.12**	**0.13**	**0.14**	**0.16**	**0.13**	**0.21**	**0.21**	**0.18**	**0.18**	0.03	0.05	0.04	1.71
C_i		0.76	0.73	0.95	0.91	1.01	0.86	1.69	1.68	1.59	1.59	0.36	0.63	0.60	

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength)).

Table 5.12. Direct, indirect relations and type for the 13 sub-criteria of MPRIs

MPRI's		R_i	C_i	$R_i + C_i$	$R_i - C_i$	Type
TP	**QPL**	0.927	0.764	1.691	0.163	**Cause**
	ST	1.204	0.730	1.934	0.475	**Cause**
	WEx	1.238	0.952	2.189	0.286	**Cause**
PF	**WH**	1.520	0.908	2.429	0.612	**Cause**
	WS	1.491	1.009	2.500	0.482	**Cause**
	WEnv	1.736	0.860	2.596	0.876	**Cause**
NTS	**DM**	0.000	1.694	1.694	-1.694	**Effect**
	SA	0.000	1.678	1.678	-1.678	**Effect**
	CS	0.000	1.589	1.589	-1.589	**Effect**
	T&L	0.000	1.589	1.589	-1.589	**Effect**
F&S	**OA**	1.765	0.361	2.125	1.404	**Cause**
	HI	1.774	0.625	2.399	1.148	**Cause**
	BS	1.707	0.603	2.310	1.104	**Cause**

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength)).

5.5.2 The use of ANP for weighting interdependent MPRIs

The use of FDEMATEL in the previous section has identified the interdependent relationships between MPRIs (Table 5.11). However, the use of ANP aims to set the final weighting adjustment according to the interrelated factors. Based on the result shown in the total relation matrices (***T***) for the four main dimensions (Table 5.7) and for the 13 sub-criteria (Table 5.11), the researcher asked the same experts who participated in the DEMATEL survey to respond to the pairwise comparison questionnaire to rank the degree of importance in relation to the given question (see Appendix I). For instance, the experts were asked 'Which dimension has more influence on pilot's TP, PF or NTS, and how much more influence?' The same question was asked in relation to another dimension and pair of sub-criteria as follows: 'Which MPRIs have more influence on the pilot's TP, QPL or ST, and how much more influence?' According to this step, the weighted matrix for the main four dimensions are presented in Table 5.13. Any presented zero value means the factor was not interdependent with the compared factor.

Table 5.13. Four main dimensions weighted matrix

MPRIs	TP	PF	NTS	F&S
TP	0	0.3782	0.6218	0
PF	0.1071	0	0.1351	0.7578
NTS	0	0	0	0
F&S	0.1075	0.6908	0.2017	0

(**TP**: Technical Proficiency; **PF**: Personal Fatigue; **NTS**: Non-Technical Skills; **F&S**: Fitness & Strength)

In a similar way, the interdependent matrix of the 13 sub-criteria of the MPRIs can be developed by forming an unweighted super matrix (Table 5.14). The aim is to obtain the weighted super matrix (Table 5.15), and that can be done by using values shown on the unweighted super matrix from Table 5.14. For instance, the value of (TP, TP) on Table 5.13 can be multiplied by the value of TP rows of QPL, ST and WEx from Table 5.14. To illustrate this, the value of (TP, TP) on the weighted matrix on Table 5.13, is 0.34. This value is multiplied by the WEx, the third row under the TP column on Table 5.14, WEx = 1. This can be calculated as [0.34 × 1= 0.34], and this value can be seen in Table 5.15, the third row of the weighted super matrix (TP-WEx) under the first column (TP-QPL). Accordingly, the rest of the values on the weighted super matrix can be formed similarly and the values are between 0 and 1. However, if the sum of each column is not equal to one, then, the matrix must be normalised (Table 5.16).

To normalise the weighted matrix, each value was divided by the sum of the same column. To illustrate this, row ‘WEnv’ is compared with the column ‘QPL’, which is equal to (0.014). By dividing this value by the sum of the QPL column, which is equal to 0.059, the resulting value is 0.24, as shown on Table 5.16.

To form the limited matrix, the limited power of the weighted super matrix (Table 5.15), can be generated using the equation $W^{\infty} = \lim_{k \to \infty} W^{k}$ to develop the limited matrix shown in Table 5.17. The researcher used Super Decisions software (V2.8) to obtain the unweighted results, weighted results, normalised super matrix, and the limited matrices (Tables 5.14–5.16).

The results shown in Table (5.17) represent the local and global weight of the 13 MPRIs. The AHP can be used to obtain the local weight, which is the weight of each criterion with respect to the same cluster, i.e., it represents the internal interrelationship between factors. The ANP can be used to obtain the global weight, which shows the degree of interdependency of each criterion externally with respect to other clusters. For example, using data from Table 5.17, T&L, CS, and SA were ranked as significant in terms of developing a reliable pilot. Specifically, they ranked as first, second, and third with respect to the main dimension of NTS, with a global weight of 0.325, 0.142, and 0.094, respectively. Moreover, the criteria HI and WEnv ranked fourth and fifth, with a weight value of 0.091 and 0.079, respectively. The most significant factors were two main dimensions: NTS and PF. This result can be justified by the number of ship accidents during port pilotage operations caused by the factors stemming from these two main dimensions (MBIA, 2017; Hsu, 2012; Sharma et al., 2011; Havold, 2005, Hetherington et al., 2006).

The international maritime organisation (IMO) attempted to reduce the effect of fatigue by presenting a practical guide on fatigue during the 71st session of the Maritime Safety Committee (MSC) in 1999. This guide was approved at the 74th session to produce a comprehensive document of IMO fatigue management. Approximately 10 years later, the IMO has recognised the continued existence of human failure, and the fact that most accidents are not directly due to human fatigue. However, due to a rapid technological advancement on board ships, the IMO has established the amendment of MANILA 2010 on the International Convention on Standards of Training, Certification and Watch-keeping (STCW 2010) (Saeed et al., 2016). One of the main changes that the convention features is a new training requirement that aims to enhance the non-technical skills of all seafarers serving on board ships, which confirms the need to maintain higher levels of NTS to ensure higher levels of operator reliability. The significance of this study is that it identifies the degree of interrelationships among these criteria in order to predict the degree of influence on a criterion when a failure exists in another criterion. For instance, having higher level of NTS with higher level of fatigue means lower reliability and unsafe operations. As a result, this model aims to assess the reliability of a marine pilot to assist decision makers in taking steps toward insuring safer operational outcomes.

Table 5.14. Unweighted super matrix for the 13 sub-criteria of MPRIs

MPRIs		**TP**			**PF**			**NTS**				**F&S**		
		QPL	**ST**	**WEx**	**WH**	**WS**	**WEnv**	**DM**	**SA**	**CS**	**T&L**	**OA**	**HI**	**BS**
TP	**QPL**	0	0	0	0	0.195	0.805	0.084	0.145	0.231	0.541	0	0	0
	ST	0	0	0	0.230	0.145	0.626	0.081	0.189	0.192	0.534	0	0	0
	WEx	0	0	0	0.269	0.324	0.407	0.060	0.150	0.198	0.592	0	0	0
PF	**WH**	0	0	1	0	0	0	0.062	0.179	0.296	0.463	0.234	0.447	0.319
	WS	0	0	1	0	0	0	0.064	0.245	0.312	0.380	0	0.622	0.378
	WEnv	0.129	0.583	0.289	0	0	0	0.050	0.125	0.268	0.558	0	0.555	0.445
NTS	**DM**	0	0	0	0	0	0	0	0	0	0	0	0	0
	SA	0	0	0	0	0	0	0	0	0	0	0	0	0
	CS	0	0	0	0	0	0	0	0	0	0	0	0	0
	T&L	0	0	0	0	0	0	0	0	0	0	0	0	0
F&S	**OA**	0.155	0.143	0.701	0.146	0.320	0.534	0.064	0.106	0.241	0.589	0	0	0
	HI	0.123	0.390	0.487	0.220	0.412	0.368	0.085	0.104	0.191	0.622	0	0	0
	BS	0.141	0.319	0.540	0.188	0.394	0.419	0.102	0.172	0.268	0.458	0	0	0

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength)).

Table 5.15. Weighted super matrix for the 13 sub-criteria of MPRIs

MPRIs		**TP**			**PF**			**NTS**				**F&S**		
		QPL	**ST**	**WEx**	**WH**	**WS**	**WEnv**	**DM**	**SA**	**CS**	**T&L**	**OA**	**HI**	**BS**
TP	**QPL**	0	0	0	0	0.074	0.305	0.052	0.090	0.143	0.336	0	0	0
	ST	0	0	0	0.087	0.055	0.237	0.053	0.118	0.120	0.332	0	0	0
	WEx	0	0	0	0.102	0.123	0.154	0.037	0.093	0.123	0.368	0	0	0
PF	**WH**	0	0	0.107	0	0	0	0.008	0.024	0.040	0.063	0.177	0.339	0.242
	WS	0	0	0.107	0	0	0	0.009	0.033	0.042	0.051	0	0.471	0.287
	WEnv	0.014	0.062	0.031	0	0	0	0.007	0.017	0.036	0.075	0	0.420	0.337
NTS	**DM**	0	0	0	0	0	0	0	0	0	0	0	0	0
	SA	0	0	0	0	0	0	0	0	0	0	0	0	0
	CS	0	0	0	0	0	0	0	0	0	0	0	0	0
	T&L	0	0	0	0	0	0	0	0	0	0	0	0	0
F&S	**OA**	0.017	0.015	0.075	0.101	0.221	0.369	0.013	0.021	0.049	0.119	0	0	0
	HI	0.013	0.042	0.052	0.152	0.284	0.254	0.017	0.021	0.038	0.125	0	0	0
	BS	0.015	0.034	0.058	0.130	0.272	0.289	0.021	0.035	0.054	0.092	0	0	0
Sum		0.059	0.153	0.430	0.572	1.029	1.608	0.217	0.452	0.645	1.561	0.177	1.230	0.866

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength)).

Table 5.16. Normalised super matrix for the 13 sub-criteria of MPRIs

MPRIs		**TP**			**PF**			**NTS**				**F&S**		
		QPL	**ST**	**WEx**	**WH**	**WS**	**WEnv**	**DM**	**SA**	**CS**	**T&L**	**OA**	**HI**	**BS**
TP	**QPL**	0.00	0.00	0.00	0.00	0.07	0.19	0.24	0.20	0.22	0.22	0.00	0.00	0.00
	ST	0.00	0.00	0.00	0.15	0.05	0.15	0.24	0.26	0.19	0.21	0.00	0.00	0.00
	WEx	0.00	0.00	0.00	0.18	0.12	0.10	0.17	0.21	0.19	0.24	0.00	0.00	0.00
PF	**WH**	0.00	0.00	0.25	0.00	0.00	0.00	0.04	0.05	0.06	0.04	1.00	0.28	0.28
	WS	0.00	0.00	0.25	0.00	0.00	0.00	0.04	0.07	0.07	0.03	0.00	0.38	0.33
	WEnv	0.24	0.41	0.07	0.00	0.00	0.00	0.03	0.04	0.06	0.05	0.00	0.34	0.39
NTS	**DM**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	SA	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	T&L	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F&S	**OA**	0.29	0.10	0.17	0.18	0.21	0.23	0.06	0.05	0.08	0.08	0.00	0.00	0.00
	HI	0.22	0.27	0.12	0.27	0.28	0.16	0.08	0.05	0.06	0.08	0.00	0.00	0.00
	BS	0.25	0.22	0.13	0.23	0.26	0.18	0.10	0.08	0.08	0.06	0.00	0.00	0.00
Total		1	1	1	1	1	1	1	1	1	1	1	1	1

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength)).

Table 5.17. Ranking for the 13 sub-criteria of MPRIs

Goal	Sub-level	MPRIs	AHP			ANP		
			LW	GW	Ranking	GW	NW	Ranking
Pilot Reliability	**TP** (0.045)	**QPL**	0.183	0.021	11	0.004	0.089	13
		ST	0.452	0.052	6	0.013	0.289	11
		WEx	0.365	0.042	9	0.028	0.622	10
	PF (0.186)	**WH**	0.113	0.050	8	0.039	0.210	9
		WS	0.547	0.243	1	0.068	0.366	6
		WEnv	0.340	0.151	2	0.079	0.424	5
	NTS (0.606)	**DM**	0.074	0.027	10	0.045	0.075	8
		SA	0.169	0.062	5	0.094	0.155	3
		CS	0.400	0.146	3	0.142	0.234	2
		T&L	0.357	0.130	4	0.325	0.536	1
	F&S (0.163)	**OA**	0.111	0.008	13	0.008	0.049	12
		HI	0.204	0.015	12	0.091	0.558	4
		BS	0.685	0.051	7	0.064	0.393	7

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength)).

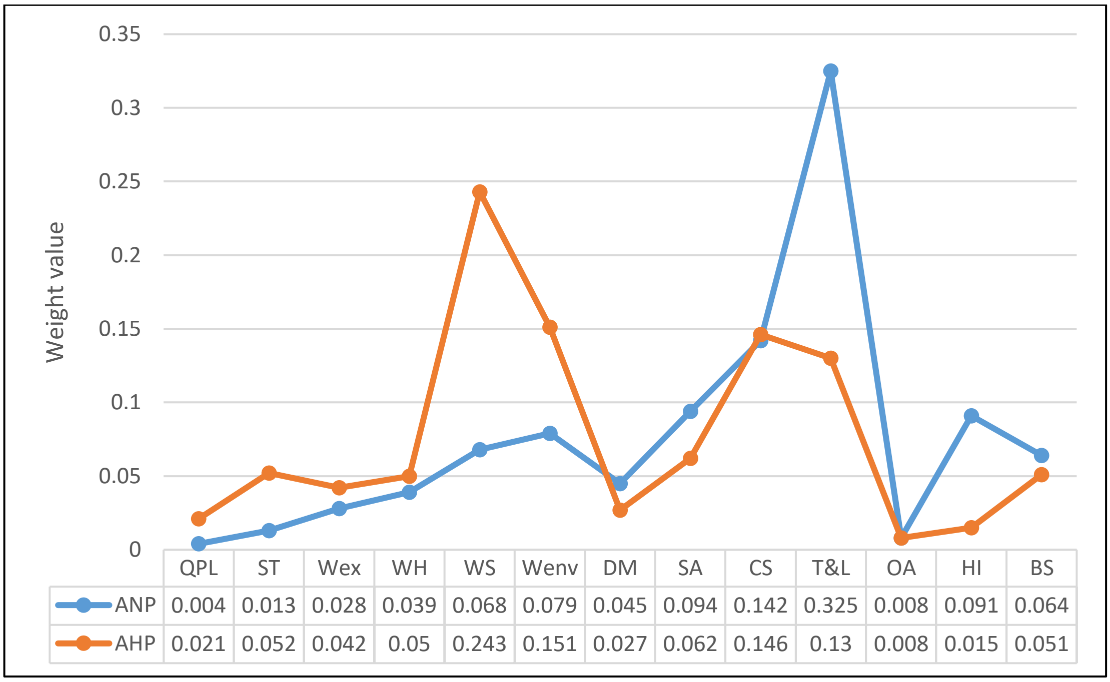

Figure 5.7. AHP and ANP Global weight flowchart for the 13 sub-criteria of MPRIs

5.6 Conclusion

This chapter examined the MPRIs identified in previous chapters with respect to the degree of interdependency among factors by using a hybrid approach. Previous studies on human reliability treat the identified factors independently (e.g., Riahi et al., 2012). This study has addressed the gap by focusing on developing an effective reliability measurement tool in an integrated form by addressing the significant factors as a set that influence the reliability of a marine pilot, and the degree of interdependency among them. Therefore, this is a new hybrid approach combining FDEMATEL and ANP methodology. Using the FDMATEL helps the decision makers to understand how factors that constitute reliability of the operator affect each other and therefore how they affect the reliability of a marine pilot during the port pilotage operation. The use of the DEMATEL approach provides a smart approach for decision makers to assess potential factors that affect an operator's reliability by dividing them into groups of cause and effect. Moreover, understanding the nature of human interactions in addition to the operational hazards that initiate a vague working environment has increased the difficulties involved in making proper decisions and, in turn, signified the need to incorporate a fuzzy sets approach to handle the imprecise and vague judgements of group decision making. The direct and indirect relation matrices, relative importance, global and local weights of each cluster, and the sub-criteria constituting these clusters were examined to clarify the degree of interdependency amongst the identified factors.

Thus, amongst the four main dimensions, the most influential factors were NTS followed by PF, F&S, and TP, respectively. Moreover, PF, TP, and F&S clusters are the cause factors, while the NTS considered as the effect cluster. This means that, the NTS has a direct influence on the pilot's TP, PF, and F&S, but the TP, PF, and F&S have a direct effect on the pilot's NTS. This can be seen in Table 5.11, where the degree of interdependency among the sub-criteria are compared in terms of clusters. The shaded cells show the relationships among the factors, which in turn are examined under the method of ANP, which aims to set the final weighting adjustment according to the identified interrelated factors towards developing a reliable marine pilot. The next chapter examines the validity of the proposed model through case studies done on three marine pilots in a major marine port to synthesise the evaluation of quantitative and qualitative MPRIs in relation to their weights using a fuzzy evidential reasoning (FER) approach.

Chapter Six: Quantities Analysis of a Marine Pilot's Reliability Using Fuzzy Evidential Reasoning (FER) approach

6.1 Chapter Summary

This chapter proposes a novel assessment tool based on the concept of the fuzzy evidential reasoning (FRE) approach to assess the reliability of a marine port pilot. The proposed method is able to deal with uncertainties raised due to the subjective judgement involved in this assessment. Previous chapters have identified, ranked, and highlighted the degree of interdependency among the main criteria shaping the proposed MPRIs. Results obtained from previous chapters are incorporated into this chapter to conduct an empirical reliability assessment. Three senior marine port pilots are involved in the reliability assessment in this work to validate the proposed research framework. The results indicate the effectiveness of the proposed method for assessing the reliability of a marine pilot at a major marine port. The proposed reliability assessment framework is presented in Figure 6.1.

Figure 6.1. Reliability assessment framework

6.2 Introduction

In every dynamic working environment, team reliability is vital, requiring operators to be continually monitoring situations and adjusting their decisions accordingly (Rouse et al., 1992). Decision-making is a central process in all organisations, and a successful operation requires a reliable team. For a team conducting a pilotage operation, variation in the decision-making process can be expected due to the dissimilarity of operators' responsibilities (Rouse et al., 1992). Therefore, a generic MPRI assessment model is proposed in this study to assess the reliability of a marine pilot during marine port pilotage operations.

Following the development of the MPRIs, the selection of criteria (see Chapter 3) was endorsed using a confirmatory assessment tool and ranked in accordance to their importance as an independent form of influence (see Chapter 4). This endorsement was followed by the identification of interdependency among criteria (see Chapter 5) in order to re-rank the criteria based on their interactions. This resulted in constructing a generic assessment model, as shown in Figure (6.2). The model consists of three levels. Level 1 represents the goal of this study, which is assessing the reliability of a marine pilot within port pilotage operations. Level 2 consists of four main factors that are directly involved in shaping an operator's reliability within the operation. Within each individual main factor are sub-factors that shape out the main factor, as presented in Level 3. In the last level, a proposed index for each sub-factor is presented, aiming to help point out the influencing factors in detail. These indices will help the decision-makers predict the development of an error in ample time and to take appropriate action.

This chapter aims to transform the results from the lower level MPRIs toward assessing the reliability of a marine pilot by synthesising the lower level towards the upper level by employing the proposed methods of FER and utility theory. This chapter discusses in brief the background of the research methods used in the first stage. It then presents the algorithms of the method with an explanation of their use. Then, a real assessment application of a marine pilot takes place. Finally, a discussion of the research outcomes is presented.

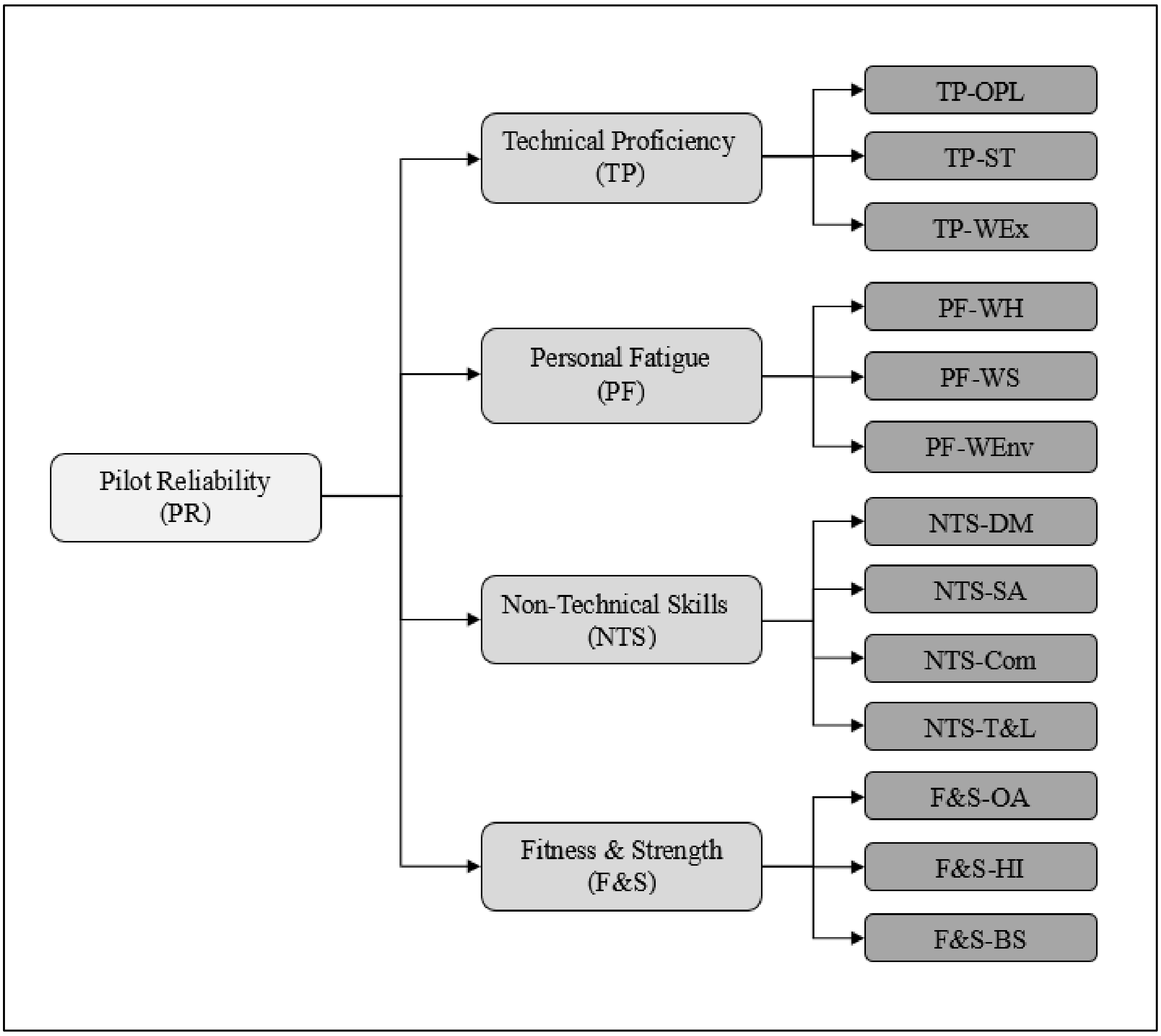

Figure 6.2. Generic model for pilot reliability

6.3 Research background

Developing a generic model enables decision-makers to understand the marine pilotage process, where the nature of the pilotage operation is characterised as complex in nature. However, as far as the marine pilot is concerned in this study, operational information and statistical data on how to assess the reliability of a marine pilot in a complex working environment are scarce. Therefore, selecting a reliable marine pilot to conduct the operation safely and efficiently based on the proposed MPRIs, rather than adapting a traditional approach, is a challenging process, and generating novel and informed methodologies is urgent.

When solving complex problems, it is essential to employ an appropriate method that is able to handle operational complexity. In this research, the use of the ER and fuzzy logic (i.e. fuzzy set theory) seems an appropriate way to cope with the complexity of fuzzy information obtained through multiple sources. This combination helps to process both crisp and fuzzy information simultaneously.

The following section contains a brief overview of the selected methods and their application in the literature.

6.3.1 Fuzzy logic (FL)

Fuzzy logic (FL) is a superset of conventional Boolean logic with extensions to account for imprecise or vague information that is capable of dealing with uncertainties (Zadeh, 1975). It permits using vague information and concepts in an exact mathematical manner (Riahi et al., 2012). In a fuzzy assessment environment, the grades used for assessment are normally formed by fuzzy numbers rather than crisp values (Ha and Yang, 2017). Fuzzy assessment studies use linguistic variables, which are a useful tool for modelling fuzzy working environments and one of the most recognised approaches in decision systems where experts are involved.

The principle on which FL is based is that every crisp value is relevant to all sets of fuzzy numbers by the degree of membership (Riahi, 2010). The use of a membership function helps when dealing with inherent ambiguity when describing an event. Fuzzy sets and fuzzy rule based techniques are used to treat uncertainty under FL. The use of these two techniques depends on the assessment situation and they are widely used by scholars across different disciplines. Most fuzzy techniques are developed using the fuzzy sets theory (FST) (Lee, 1990; Yen and Langari, 1999; Mendel, 2001).

6.3.2 Fuzzy set theory (FST) and fuzzy membership function

Since the notion of FL was introduced, one of the aims of FST is to formulate a methodological solution for complex or ill-defined problems in order to assess the problem when using conventional techniques (Kandel, 1986). When measuring uncertain variables, crisp variables cannot be expressed in a formal way, but using fuzzy forms when assessing variables enables the gradual transition between assessment states to overcome uncertain expressions (Wang, 2003). Using linguistic variables helps when describing assessment parameters, where the subjective nature of the information helps measure the parameters in a more convenient way. These linguistic terms (i.e. very high, high) are necessary media that can be used to describe contentious and overlapping states (Riahi, 2010). This helps to incorporate qualitative and imprecise reasoning statements when dealing with fuzzy algorithms. The linguistic terms are further defined in terms of fuzzy membership functions. A membership function is a set of objects mapped as a membership degree ranging between 0 and 1. The linguistic variables can be easily defined in terms of a simple form of a membership function (i.e. triangular, trapezoidal). This theory allows incorporating mathematical operators and programming to apply to the fuzzy domain (Mokhtari et al., 2012). Thus, a membership function is expected to be flexible in terms of its definition to suit various circumstances in allowing the decision-makers to interpret subjective information represented as input variables in more convenient way.

There are different shapes of membership functions, namely triangular, trapezoidal, S curves, bell curves, Gaussian curves, piecewise linear and π curves (Ramin et al., 2012;

Aziz, 2009; Madau et al., 1996). The most commonly used shapes in the literature are triangular and trapezoidal because of their ease of use (Ertugrul and Karaksouglu, 2007; Mokhtari et al., 2012; Bloch and Maitre, 1995). Developing a suitable membership function is highly dependent on a psychometric scale chosen by the model builder (Liu et al., 2012; Liu et al., 2005; Sii et al., 2005); it can be based on the model builder's knowledge of the problem, historical system records, and the help of experts. The psychometric scale is a subjective scale composed of a range of granularity and fine detail (Ishola, 2017). For the purpose of this study, the psychometric scale used to develop the membership function is developed based on expert consultation, port requirements, and knowledge acquisition through literature (Liu et al., 2005; Riahi et al., 2012; Gaonkar et al., 2013).

6.3.3 Fuzzy rule-based logic

Fuzzy rule-based logic, known as a knowledge-based or rule-based logic, produces simpler, more intuitive, and better-behaved models. It is comprised of the set of a realistic subjective assessment approach based on fuzzy IF-THEN rules (Yang et al., 2009; Sii et al., 2001). Because an IF-THEN rule is capable of implementing a conditional statement easily and efficiently in a more reasonable manner, it is considered the core of a FL system (Ha et al., 2017). According to Yang et al. (2009), unavailable or incomplete objective data that helps with analysing the highlighted topic requires employing a realistic subjective assessment approach based on fuzzy IF-THEN rules in FST. Thus, the assessment is subject to conditional parts and contains linguistic variables capable of modelling the qualitative features of human knowledge and reasoning processes without employing precise quantification analysis (Yang et al., 2009; Sii et al., 2001). This process enables the assessor to handle the linguistic information that is commonly used for safety assessment, since it provides a useful assessment tool that is capable of dealing with this type of information (Sii et al., 2001). The IF-THEN rule consists of two parts: an antecedent (i.e. fuzzy inputs) and a consequent (i.e. fuzzy output) (Pillay and Wang, 2003). According to Sii et al. (2001), the fuzzy rule-based logic has several useful properties, since the rules can be formulated linguistically rather than in numerical form. Moreover, they are often expressed based on fuzzy conditional statements based on IF-THEN rules, which can be easily implemented. Accordingly, the fuzzy rules based on IF-THEN rules can be expressed as follows (Yang et al., 2009; Liu et al., 2005):

$$R^k: IF x_1 is A_1^k and \dots . and\ x_n is\ A_n^k, THEN\ y\ is\ B^k \tag{6.1}$$

This form of statement is a multi-input-single-output case, in which $A_1^k \dots . A_n^k$ and B^k represent the sets of fuzzy inputs and fuzzy output, respectively. $x_1 \dots . x_n$and y represent the input and output linguistic variables of the fuzzy sets, respectively.

In this study, when using FER to assess the reliability of a marine pilot, the expression of the qualitative input and output can achieve a degree of belief when using linguistic variables (Yeo et al., 2014; Ha et al., 2017). Accordingly, Equation 6.2 can be expressed as follows:

$$R^k: IF A_1^k is A_2^k and \dots . and\ A_n^k, THEN\ \{(H_1, B_1^k), \dots ., (H_M, B_M^k)\}$$

$$\textstyle\sum_{j=1}^{M} B_j^k \leq 1 \tag{6.2}$$

Where A_1^k represents the linguistic terms used for i^{th} antecedent MPRI used in the k^{th} rule (R^k), and B_j^krepresents the degree of belief that belongs to linguistic term H_j.

6.3.4 Fuzzy logic application

FL has been applied widely across different disciplines. Liu et al. (2005) applied a fuzzy rule-based approach in conjunction with ER for modelling the safety system of an engineering system or project. Sii et al. (2001) developed a qualitative safety model for maritime systems based on the FL approach. Riahi et al. (2012) assessed the reliability of seafarers using a FL approach in a hybrid form with ER. Yang et al. (2009) assessed the security of a maritime transport system using a fuzzy evidential reasoning approach. Alyami et al. (2014) evaluated the criticality of hazardous events in container terminals using a fuzzy rule-based Bayesian Network (FRBN) approach. Yang et al. (2008) used FRBN to prioritise failures in a failure mode and effect analysis (FMEA). Wang et al. (2009) used fuzzy weighted geometric means to evaluate risks in FMEA. Li et al. (2010) used a fuzzy logic-based approach to identify human error risk importance.

6.3.5 Mapping process

Following the determination of the fuzzy estimate for the attributes of each MPRI element, the measurement of reliability includes different numbers and linguistic variables in the lower level of the proposed MPRIs. The associated upper level also includes different grades of belief. Since assessing the reliability of an expert cannot be estimated precisely, especially in a fuzzy situation, transforming fuzzy information into a belief degree can provide the same grades of evaluation that represent the reliability profile of the attribute associated with each MPRI. It is essential to transform the assessment grades and variables into a concise format for assessing their associated upper criterion (Yeo et al., 2014). The application of ER requires the assessment grades to be in the same universe; therefore, the mapping process approach has been proofed for use in transforming qualitative and quantitative fuzzy input data into their upper associated criteria in a form of fuzzy output (Ha et al., 2017; Yeo et al., 2014; Riahi et al., 2012; Yang et al., 2009). The mapping process can help capture any ambiguity and uncertainty resulting from an expert's subjectivity. The fuzzy IF-THEN rule, developed by Yang (2001), is the most suitable technique for transforming fuzzy input to fuzzy output. The input of $l^i(\sum_{i=1}^{n} l^i \leq 1)$, indicates the fuzzy input associated with one of the lower levels of the MPRIs, while $O^j(O^j = \sum_{i=1}^{n} l^i \beta_i^j)$ represents the fuzzy output transformed from l^i. The degree of belief (B_i^j) can be formed based on the experts' judgement, representing the degrees of relationship among given assessment grades between different levels, and must be equal to 1 ($\sum_{i=1}^{n} \beta_i^j = 1$) (see Figure 6.3). For instance, let us assume the assessment grades of one of the upper level MPRIs, 'Personal Fatigue (PF)', is evaluated using the linguistic variables 'Neutral', 'Slightly Fatigued', 'Moderate', 'Fatigued', and 'Very Bad', while the qualitative assessment grades used to assess the sub-level of PF 'Working Hours (WH)' that influencing PF is evaluated as 'Very Good', 'Good', 'Moderate', 'Bad', and 'Very Bad'. Assigning the fuzzy rule, in this case, is usually based on the decision-makers, who have considerable experience within the field of assessment. Assigning the fuzzy rules helps map fuzzy inputs to fuzzy outputs (See Figure 6.3). The relationships between fuzzy inputs and fuzzy outputs can be evaluated using the following equations:

$$\sum_{j=1}^{5} \beta_1^j = 1, \sum_{j=1}^{5} \beta_2^j = 1, \sum_{j=1}^{5} \beta_3^j = 1, \sum_{j=1}^{5} \beta_4^j = 1, \sum_{j=1}^{5} \beta_5^j = 1 \qquad (6.3)$$

$$O^j = \sum_{i=1}^{5} l^i \beta_i^j \qquad (6.4)$$

$$\sum_{i=1}^{5} l^i \leq 1 \qquad (6.5)$$

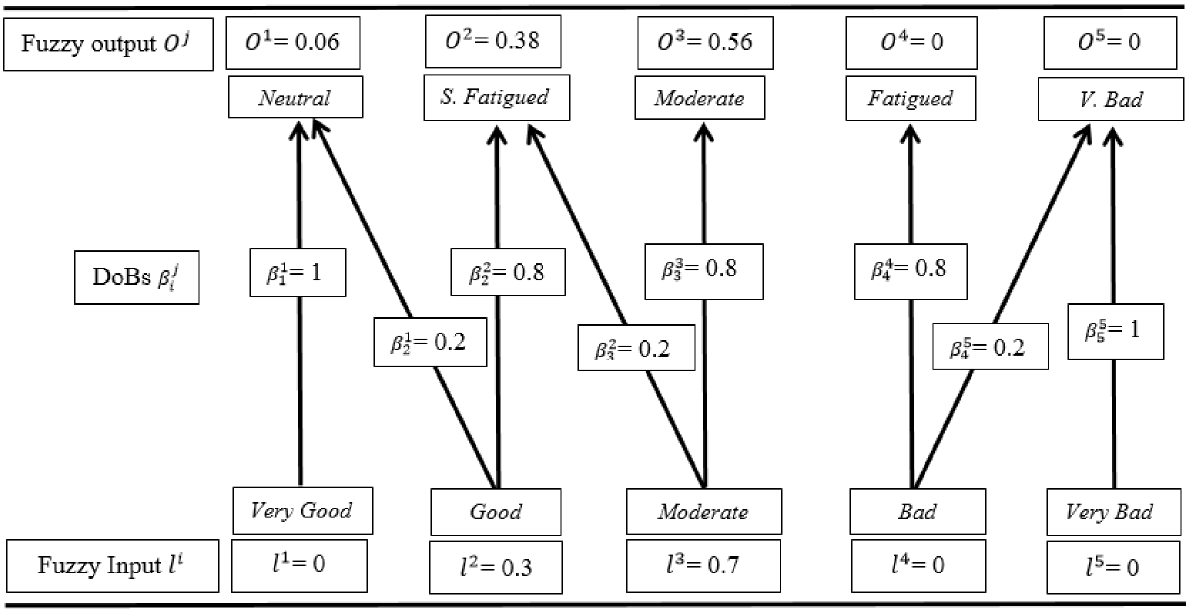

Figure 6.3. Example of fuzzy mapping process

6.3.6 Evidential reasoning (ER) approach

The ER approach is one of the most powerful MCDM tools when used under uncertain assessment environments. This theory of evidence was established by Dempster (1968) and further improved by Shafer (1976), and is known as the Dempster-Shafer (D-S) theory of evidence. It was originally used for data aggregation as an approximate reasoning tool in an expert system (Dubois and Prade, 1991). It has also been used to make operational decisions under uncertainty by exploiting an expert's knowledge and experience in the form of belief functions (Yang, 2001; Riahi et al., 2012).

The development of the ER approach began in the 1990s, following a need to deal with a hybrid form of data that had both qualitative, and quantitative attributes found in MCDM problems under uncertainties (Yang and Singh, 1994). The ER approach was further updated by Yang and Sen (1994), and then further modified by Yang (2001). Yang and Xu (2002) generated new ER algorithms. Since then, ER has been applied widely in literature across different disciplines. The main advantages of using the ER approach are as follows (Yang, 2006):

- It is capable of handling incomplete, uncertain, and vague, as well as complete and precise, data.
- It allows ER users to express their judgments subjectively and quantitatively in a more flexible way.
- It is capable of accommodating or representing the uncertainty and risks inherent in the decision analysis.
- As a hierarchical evaluation process, it offers a rational and reproducible methodology to aggregate the assessed data.
- It can easily obtain the assessment output using mature computing software called an intelligent decision system (IDS). (Yang and Xu, 2002).

The process of aggregating criteria when using the ER approach is a non-linear process when compared to a traditional weighting assignment that other MCDM approaches employ (Riahi, 2010). The non-linearity is decided by the weights of the criteria and the way each criterion is assessed. In addition, the framework of the ER approach provides not only a flexible description of an MCDM problem, but also helps prevent information loss when converting the distribution into a single value in the modelling process. Handling incomplete information requires establishing utility intervals to describe the impact of the missing information on the decision analysis. This helps provide a basis to improve the originality of the data and to conduct sensitivity analysis.

Several applications of the ER approach have been addressed in the literature (Wang et al., 1996; Yang et al., 2009; Liu et al., 2011; Mokhtari et al., 2012; Ha et al., 2017). Some studies contribute towards the use of ER in representing and managing uncertainty in decision-making processes, such as port selection (Yeo et al., 2014), assessing the reliability of seafarers (Riahi et al., 2012), executive car assessment (Yang and Xu, 2002), human error probability quantification (Xi et al., 2017), assessing the risk of seaports (John et al., 2014), safety analysis and synthesis (Wang et al., 1996), and vessel selection (Yang et al., 2009). As seen in the identified studies, using FER can provide a useful tool for evaluating the reliability of a marine pilot under uncertain working environments. The following section discusses the application of FER in evaluating the reliability of three senior marine pilots during pilotage operations on the selected port of this study.

6.3.7 Evidential reasoning algorithm

The use of the ER approach in this research was employed for aggregating all the outputs of the degrees of belief (DoB) derived from each fuzzy rule to generate a conclusion. The first step of the ER process is to transform the DoB into two parts of basic probability mass (i.e. individual assigned and unassigned belief degrees) in order to aggregate all the output from each fuzzy rule into a combined set of DoB. To explain the application of the algorithms, let's suppose 'R' represents a set group of five reliability expressions synthesised by two evaluators using two sub sets, 'R_1' and 'R_2'. The following reliability expressions based on their judgements are:

$$R = \{\beta^1 V.Low, \beta^2 Low, \beta^3 Medium, \beta^4 High, \beta^5 V.High\}$$

$$R_1 = \{\beta_1^1 V.Low, \beta_1^2 Low, \beta_1^3 Medium, \beta_1^4 High, \beta_1^5 V.High\}$$

$$R_2 = \{\beta_2^1 V.Low, \beta_2^2 Low, \beta_2^3 Medium, \beta_2^4 High, \beta_2^5 V.High\}$$

Where:

'V. Low', 'Low', 'Medium', 'High', and 'V. High' are the reliability terms associated with their DoBs, used to describe the status of the assessed target.

The normalised comparative weight can be evaluated based on the selected weighing techniques, such as simple rating methods or based on pairwise comparison techniques such as ANP or AHP, as suggested by Yang et al. (2001). The normalised relative weight is given as $\omega_1$and $\omega_2(\omega_1 + \omega_2 = 1)$. $M_1^m$and M_2^m(m =1,2,3,4 or 5) are single degrees that constitute R_1 and R_2, which helps the assumption that the reliability estimation is set to the five reliability terms. Therefore, obtaining $M_1^m$and M_2^m can be obtained using Equation (6.6):

$$M_{\mathrm{j}}^m = \omega_{\mathrm{j}}\beta_{\mathrm{j}}^m \tag{6.6}$$

Where:

M_{j}^m $(j = 1, \dots, N; m = 1, \dots, \mathrm{L})$ denotes an individual degree for each fuzzy rule that supports the aggregation of R that is assessed using the terms of DoB. ω_{j} indicates the relative importance of MPRIs. Based on the above example, $M_1^m$and M_2^mcan be found as follows:

$$M_1^m = \omega_1\beta_1^m$$

$$M_2^m = \omega_2\beta_2^m$$

Where: $m = 1, 2, 3, 4,$ or 5.

The unassigned, individual remaining belief values for $M_{H_j}$are the following:

- The remaining belief degrees ($\bar{M}_{H_j}$) that are not assigned to any individual evaluation grades caused by the relative importance.
- The remaining belief degrees ($\tilde{M}_{H_j}$) that are not assigned to any individual evaluation grades caused by incomplete assessment in subset R.

This can be presented by Equation (6.7):

$$M_{H_j} = \bar{M}_{H_j} + \tilde{M}_{H_j} \tag{6.7}$$

Where:

M_{H_j}($j = 1, \dots, N; m = 1, \dots, \mathrm{L}$)

To find out $\bar{M}_{H_j}$, and $\tilde{M}_{H_j}$, the following equation is applied:

$$\bar{M}_{H_j} = 1 - \omega_{\mathrm{j}} \tag{6.8}$$

$$\widetilde{M}_{H_j} = \omega_{\mathrm{j}}(1 - \textstyle\sum_{j=1}^{\mathrm{n}} \beta_{\mathrm{j}}^{m}) \tag{6.9}$$

Therefore, for the above example, by using Equations (6.7-6.9), M_{H_j}, $\bar{M}_{H_j}$, and $\widetilde{M}_{H_j}$, can be obtained with:

$$\bar{M}_{H_1} = 1 - \omega_1 = \omega_2$$

$$\bar{M}_{H_2} = 1 - \omega_2 = \omega_1$$

$$\widetilde{M}_{H_1} = \omega_1\left(1 - \sum_{m=1}^{5} \beta_1^m\right) = \omega_1[1 - (\beta_1^1 + \beta_1^2 + \beta_1^3 + \beta_1^4 + \beta_1^5)]$$

$$\widetilde{M}_{H_2} = \omega_2\left(1 - \sum_{m=1}^{5} \beta_2^m\right) = \omega_2[1 - (\beta_2^1 + \beta_2^2 + \beta_2^3 + \beta_2^4 + \beta_2^5)]$$

Assuming the degree of belief for the non-normalised expressions is represented as $\beta^{m\prime}\ (m = 1, 2, 3, 4\ or\ 5)$, this can confirm the mixtures of terms used for a reliability evaluation by the two assessors involved in the evaluation.

Assuming that M'_{H_U} represents the non-normalised unassigned remaining belief of the five reliability expressions, the following equations are as follows (Yang and Xu, 2002):

$$\beta^{m\prime} = k(M_{\mathrm{j}}^{m} M_{\mathrm{j+1}}^{m} + M_{\mathrm{j}}^{m} M_{H_{j+1}} + M_{\mathrm{j+1}}^{m} M_{H_j}) \tag{6.10}$$

$$\bar{M}'_{H_U} = K(\bar{M}_{H_j} \bar{M}_{H_{j+1}}) \tag{6.11}$$

$$\widetilde{M}'_{H_U} = K(\widetilde{M}_{H_j} \widetilde{M}_{H_{j+1}} + \widetilde{M}_{H_j} \bar{M}_{H_{j+1}} + \bar{M}_{H_j} \widetilde{M}_{H_{j+1}}) \tag{6.12}$$

$$K = \left(1 - \textstyle\sum_{T=1}^{\mathrm{N}} \sum_{\substack{R=1 \\ R \neq T}}^{\mathrm{N}} M_{\mathrm{j}}^{T} M_{\mathrm{j+1}}^{R}\right)^{-1} \tag{6.13}$$

Where:

$$(m = 1, \ldots., \mathrm{N}), (j = 1, 2 \ldots, \mathrm{N} - 1)$$

Following the above two assessor illustrations, by using Equations (6.10-6.13), the following can be obtained:

$$\beta^{m\prime} = k(M_1^m M_2^m + M_1^m M_{H_2} + M_2^m M_{H_1})$$

$$\bar{M}'_{H_U} = K(\bar{M}_{H_1}\bar{M}_{H_2})$$

$$\tilde{M}'_{H_U} = K(\tilde{M}_{H_1}\tilde{M}_{H_2} + \tilde{M}_{H_1}\bar{M}_{H_2} + \bar{M}_{H_1}\tilde{M}_2)$$

$$K = \left(1 - \sum_{T=1}^{5}\sum_{\substack{R=1\\R\neq T}}^{5} M_1^T M_2^R\right)^{-1}$$

The aggregation results obtained from Equations (6.10-6.13) can be generated by assigning $\bar{M}'_{H_U}$ back to the number of expressions used in the case. Therefore, the following equation can be obtained following the normalisation process:

$$\beta^m = \frac{\beta^{m\prime}}{1-\bar{M}'_{H_U}} \; (m = 1, \ldots\ldots, \mathrm{N}) \qquad (6.14)$$

$$M_{H_U} = \frac{\tilde{M}'_{H_U}}{1-\bar{M}'_{H_U}} \qquad (6.15)$$

In the above algorithms, M_{H_U} signifies the degree of incompleteness as an unassigned extent of belief in the whole evaluation. It gives the procedures for how to combine the two groups. However, in some cases, the aggregation process may require synthesis of more than two criteria. This can be done by aggregating the third fuzzy sets with the result from the first aggregations using similar processes and equations.

6.3.8 Obtaining a crisp number using the expected utility approach

The expected utility approach is utilised to generate numerical values equivalent to the distributed assessment for the upper-level criterion, such as the goal, and to find the individual crisp number for each alternative in order to rank the alternatives accordingly. The expected utility approach was invented by Yang (2001) and is used widely to obtain crisp values for the assessed identified criteria.

To illustrate this approach, assume the utility value of H_n being assessed as $u(H_n)$ and $u(H_{n+1}) > u(H_n)$ if H_{n+1} is more desired than H_n (Yang, 2001; John et al., 2014; Zhang et al., 2016). The utility value for each given linguistic term used can be represented by $u(H_n)$, which can help estimate the utility value using the decision-maker's preferences. The evaluation grades of the utility value equidistantly distributed in a normalised utility space can be calculated as follows (Yang, 2001):

$$u(H_n) = \frac{V_n - V_{min}}{V_{max} - V_{min}} \tag{6.16}$$

where V_n is the assigned ranking value for the linguistic terminology (H_n), V_{max} is the decision-makers' most preferable linguistic term of H_N ranking value, and V_{min} is the decision-makers' least preferable linguistic term of H_1 ranking value.

$$\beta_H = 1 - \sum_{n-1}^{N} \beta_n \tag{6.17}$$

The utility value for the top criteria ($S(E)$), such as the goal, is represented as $u\big(S(E)\big)$. ($\beta_H \neq 0$) means the assessment is incomplete; therefore, a belief interval of $[\beta_n, (\beta_n + \beta_H)]$ can provide the likelihood of $S(E)$ assessed to H_n. By assuming that the lower preferable linguistic term is assigned the lowest utility value and is indicated by $u(H_1)$, while the upper preferable linguistic term is assigned with the highest utility value and is presented by $u(H_n)$, the minimum, maximum, and average utility value of $S(E)$ are identified by (Yang, 2001; Riahi et al., 2012):

$$u_{min}\big(S(E)\big) = \sum_{n=2}^{N} \beta_n u(H_n) + (\beta_1 + \beta_H)u(H_1) \tag{6.18}$$

$$u_{max}\big(S(E)\big) = \sum_{n=1}^{N-1} \beta_n u(H_n) + (\beta_N + \beta_H)u(H_N) \tag{6.19}$$

$$u_{average}\big(S(E)\big) = \frac{u_{min}\big(S(E)\big) + u_{max}\big(S(E)\big)}{2} \tag{6.20}$$

When all the assessments are completed, $\beta_H = 0$ and the maximum, average, and minimum utility values for $S(E)$ are equal. Consequently, obtaining $u\big(S(E)\big)$ can be carried out by the following equation (Yang, 2001; Zhang et al., 2016):

$$u\big(S(E)\big) = \sum_{n=1}^{N} \beta_n u(H_n) \tag{6.21}$$

The above utility values are not used for aggregation procedures; they are just to characterise the assessment (Yang and Xu, 2002; Mokhtari et al., 2012).

6.3.9 MPRI validation using sensitivity analysis

The main objective of the sensitivity analysis is to identify the degree of changes on the model caused when a minor change in inputs is made (Yang et al., 2009; Riahi et al., 2013; Xi et al., 2017). These changes can result due to a change of the parameters of the model or even a change of the degrees of belief assigned to the linguistic variables describing these parameters. However, if the methodology is able to provide a logical conclusion, then the sensitivity analysis must follow one of the following three axioms (Yang et al., 2009):

Axiom 1. A slight increase or decrease in the degree of belief associated with any linguistic variables of the lowest-level criteria will certainly result in a relative increase or decrease in the degree of belief of the linguistic variable and the preference degrees of the model output.

Axiom 2. If the degree of belief associated with the highest-preference linguistic term of the lowest-level criterion is decreased by m and n (such that the degree of belief associated with the lowest-preference linguistic term is simultaneously increased by m and n ($1 > n > m$)) and the utility values of the model output are evaluated as U_m and U_n, respectively, then U_m should be greater than U_n.

Axiom 3. If 'N' and 'K' ($K < N$) criteria from all the lowest-level criteria are selected, and the degrees of belief associated with the highest-preference linguistic terms of each N and K criterion is decreased by the same amount (i.e. simultaneously, the degrees of belief associated with the lowest-preference linguistic terms of each N and K criteria are increased by the same amount) then the utility values of the model output can be evaluated as U_K and U_N respectively, then U_K should be greater than U_N.

6.4 An empirical pilot’s reliability assessment

In this study, three senior marine pilots were selected and their reliability evaluated by three duty harbour masters (HM) using the proposed model under a fuzzy working environment. The three HMs are appointed by the port authority and have considerable years of experience as senior marine pilot. Moreover, they have master mariner class 1 (COC 1) certificates and worked for a period of time on board merchant ships. Accordingly, the result obtained highlights the applicability of the proposed model in evaluating the reliability of decision-makers to select the right pilot to conduct the pilotage service. The given information for the three senior marine pilots is presented in Table 6.1, showing the variance of their given criteria. It is worth mentioning that each pilot was assessed based on basic information such as pilot qualification, training certificates, experience, medical conditions, and age, which are available in their personal records. Moreover, pilot fatigue and non-technical skills were assessed with information obtained from HM observations. In addition, the HMs’ were involved to set the fuzzy rules required for mapping processes from the lower MPRI's towards the goal.

Table 6.1. Pilot information

MPRIs	Pilot 1	Pilot 2	Pilot 3
QPL	Diploma COC1 + PL	BSc COC3 +PL	Diploma +PL
ST	• Elementary First Aid (EFA); • Personal survival technique (PST) • Proficiency in survival craft (PSC); • Fire prevention and firefighting (FPFF); • Advanced fire prevention and firefighting (AFF) certificate; • Ship-handling simulator certificate; • Global Maritime Distress and Safety System (GMDSS) certificate; • Advanced Pilot Training (APT) certificate; and • Bridge Resource Management (BRM) training course.	• Advanced fire prevention and firefighting (AFF) certificate; • Fire prevention and firefighting (FPFF); • Elementary First Aid (EFA) certificate; • Personal survival technique (PST) • Proficiency in survival craft (PSC); • Ship-handling simulator certificate; • Advance Pilot Training (APT) certificate; and • Bridge Resource Management (BRM) training course.	• Advanced fire prevention and firefighting (AFF) certificate; • Fire prevention and firefighting (FPFF); • Elementary First Aid (EFA) certificate; • Personal survival technique (PST) • Proficiency in survival craft (PSC); • Ship-handling simulator certificate; • Advanced Pilot Training (APT) course; and • Global Maritime Distress and Safety System (GMDSS) certificate.
WEx	6 Y	13 Y	23 Y
WH	30% Good, and 70% Moderate	30% Good, and 70% Moderate	70% V. Bad, and 30% Bad
WS	70% High, and 30% V. High	60% V. High, and 40% High	40% Moderate and 60% High
WEnv	60% Good, and 40% Moderate	50% Moderate, and 50% Bad	30% Moderate, and 70% Bad
DM	20% V. Good, and 80% Good	20% Good, and 80% Average	40% V. Good, and 60% Good
SA	70% Good, and 30% Average	60% Good, and 40% Average	80% Good, and 20% V. Good
CS	70% Good, and 30% Average	20% Good, and 80% Average	50% Good, and 50% Average
T&L	80% Average, and 20% Bad	60% Good, and 40% Average	40% Average, and 60% Bad
OA	37 Y	43 Y	55 Y
HI	80% Healthy, and 20% Good	80% Good, and 20% Moderate	100% Moderate
BS	80% Fit, and 20% Good	70% Good, and 30% Moderate	80% Moderate, and 20% Weak

6.4.1 A generic model for assessing a pilot’s reliability

Subject to the generic pilotage operation reliability model presented in Section 3.7.2.4, a generic MPRI model can be developed to assess a pilot’s reliability, as shown in Figure 6.2. Each criterion was weighted using the AHP and ANP (see Section 6.3.4). The weights obtained in this section were used in aggregating the lower level to the associated upper level, followed by aggregating the main level towards the goal, as presented in Section 6.4.6. In addition, quantitative and qualitative criteria were segregated, and the linguistic term for each qualitative criterion was defined and presented in Table 6.2. These linguistic variables were used to describe the qualitative and quantitative MPRIs, which were adapted as presented in Tables 6.3-6.15.

Table 6.2. Linguistic terms used for assessment

		Linguistic terms				
Goal	**Pilot’s Reliability**	V. High	High	Moderate	Low	V. Low
Main criteria	**TP**	V. Good	Good	Average	Low	Basic
	PF	Neutral	S. Fatigued	Moderate	Fatigued	V. Bad
	NTS	V. Good	Good	Moderate	Bad	V. Bad
	F&S	Fit	Good	Moderate	Bad	Unfit
Sub-criteria	**TP-QPL**	Assessed quantitatively				
	TP-ST	Assessed quantitatively				
	TP-WEx	Assessed quantitatively				
	PF-WH	V. Good	Good	Moderate	Bad	V. Bad
	PF-WS	V. Low	Low	Moderate	High	V. High
	PF-WEnv	V. Good	Good	Moderate	Bad	V. Bad
	NTS-DM	V. Good	Good	Average	Bad	V. Bad
	NTS-SA	V. Good	Good	Average	Bad	V. Bad
	NTS-CS	V. Good	Good	Average	Bad	V. Bad
	NTS-T&L	V. Good	Good	Average	Bad	V. Bad
	F&S-OA	Assessed quantitatively				
	F&S-HI	Healthy	Good	Moderate	Bad	Sever
	F&S-BS	Fit	Good	Moderate	Weak	V. Weak

Table 6.3. Linguistic grades description for qualification and pilotage licensing (QPL)

Linguistic variables	Description	References
Uppermost	Certificate of Competency class 1 (COCI)	Riahi et al., 2012; Board, 1994; Port standard
2nd Higher	Certificate of Competency class 2 (COCII)	
Average	Certificate of Competency class 3 (COCIII)	
2nd minimum	Certificate of Competency class 4 (COCIIII)	
Minimum	Marine Diploma or BSc in nautical science + pilotage license	

Table 6.4. Linguistic grades description for special training (ST)

Linguistic variables	Description	References
Well Trained	Have a valid minimum port requirement plus more than 3 additional recommended courses, ≥9 out of 10	Riahi et al., 2012; Port standard
Trained	Have a valid minimum port requirement plus 3, 8 out of 10	
Average	Have a valid minimum port requirement plus 2, 7 out of 10	
Low	Have a valid minimum port requirement plus 1, 6 out of 10	
Basic	Have a valid minimum port requirement 5 out of 10	

Table 6.5. Linguistic grades description for working experience (WEx)

Linguistic variables	Description	References
Very High	≥ 20 Years	Riahi et al., 2012; Port standard
High	16 – 20 Years	
Average	11 – 15 Years	
Low	6 – 10 Years	
Very Low	0 – 5 Years	

Table 6.6. Linguistic grades description for working hours (WH)

Linguistic variables	Description	References
V. Good	Works within the official working hours, had very good rest between the operations, had very good sleep before the duty, works at a fixed shift of day time	Iwasaki et al., 1998; Dembe et al., 2005; Raby and McCallum, 1997; Embriaco et al., 2007; Folkard et al., 2007; park et al., 2001; Parkes, 1998
Good	Works just above the official working hours, had good rest between the operations, had good sleep before the duty, always works at a day time shift with few night shift	
Moderate	Works moderate hours above the official working hours, had average rest between the operations, had average sleep before the duty, works in a rotation shifts day and night	
Bad	Overloaded with an extended hours above the official working hours, had little rest between the operations, had little sleep before the duty with accumulated fatigue, works at night shift with few days of day shift	
V. Bad	Overloaded with a contentious hours above the official working hours, had no rest between the operations, had very little sleep before the duty with a severe accumulated fatigue, always works at night shift	

Table 6.7. Linguistic grades description for working stresses (WS)

Linguistic variables	Description	References
V. Low	Subject to normal workloads and physical demands, works in normal working condition, gained very good support from the management and other team members, works within the designated working hours.	Quick et al., 1997; Kim et al., 2009; Sneddon et al., 2013; Parkes, 1998
Low	Subject to slight increase in workloads and physical demands, works in good working condition, gained enough support from the management and other team members, works with a slight extend on the designated working hours.	
Moderate	Subject to moderate increase in workloads, works in moderate working condition, gained moderate support from the management and other team members, works with moderate extend on the designated working hours.	
High	Subject to high increase in workloads and physical demands, works in bad working condition, gained little support from the management and other team members, works with high extend on the designated working hours.	
V. High	Subject to adverse increase in workloads and physical demands, works in adverse working condition, gained very little or no support from the management and other team members, works with extreme extend on the designated working hours.	

Table 6.8. Linguistic grades description for working environment (WEnv)

Linguistic variables	Description	References
V. Good	Excellent physical places for rest, excellent weather and sea conditions, excellent managerial practices and safety consideration, excellent relation with the management and other team members.	Celik and Cebi, 2009; Riahi et al., 2013; Saeed et al., 2016; Bhattacharya and Tang, 2013; Darbra et al., 2007
Good	Good physical places for rest, good weather and sea conditions, good managerial practices and safety consideration, good relation with the management and other team members.	
Moderate	Average physical places for rest, average weather and sea conditions, average managerial practices and safety consideration, average relation with the management and other team members.	
Bad	Bad physical places for rest, bad weather and sea conditions, bad managerial practices and safety consideration, bad relation with the management and other team members.	
V. Bad	Very bad or no places for rest, adverse weather and sea conditions, very bad managerial practices and safety consideration, adverse relation with the management and other team members.	

Table 6.9. Linguistic grades description for decision-making (DM)

Linguistic variables	Description	References
Very Good	Perfectly gather all information to identify problem, consider and share any changes on the operation with other team members, clearly confirms and state all selected options in compliance with the port regulations to ensure port safety, and capable at carrying a complete checks of operational outcome against plan.	Yule and Brown, 2012 Flin et al., 2008; Flin et al., 2003; Orasanu and Connolly, 1993
Good	Gathering sufficient pilotage information to identify problem, consider and share enough changes on the operation with other team members, state and share enough options in compliance with the port regulations to ensure port safety, and capable at carrying enough checks of operational outcome against plan.	
Average	Gathering just enough pilotage information to identify problem, consider and share some changes on the operation with other team members, state and share some options in compliance with the port regulations to ensure port safety, and carrying some checks of operational outcome against plan.	
Bad	Gathering few pilotage information to identify operational problem, consider and share few changes on the operation with other team members, state and share few options in compliance with the port regulations to ensure port safety, and carrying few checks of operational outcome against plan.	
Very Bad	The pilot never gather any information to identify operational problem, failed to consider and share all operational changes with other team members, never state and share operational options in compliance with the port regulations to ensure port safety, and never consider carrying operational outcome checks against plan.	

Table 6.10. Linguistic grades description for situation awareness (SA)

Linguistic variables	Description	References
Very Good	The pilot perfectly carrying full operational assessment to monitor operational changes and report to other team members, collect all the required information related to the operation, share and discussed all the updated operational information with other team members.	Endsley, 1995; Salmon et al., 2009; Flin et al., 2008; Johnston et al., 2011
Good	The pilot carrying sufficient operational assessment to monitor operational changes and report to other team members, collect enough information related to the operation, share and discussed enough updated operational information with other team members.	
Average	The pilot carrying reasonable operational assessment to monitor operational changes and report to other team members, collect reasonable information related to the operation, share and discussed reasonable updated operational information with other team members.	
Bad	The pilot carrying very little operational assessment to monitor operational changes and report to other team members, collect very few information related to the operation, share and discussed very brief updated operational information with other team members.	
Very Bad	The pilot never carry operational assessment, do not monitor and report operational changes with other team members, never collect the required information related to the operation, never share and discussed any updated operational information with other team members.	

Table 6.11. Linguistic grades description for communication skills (CS)

Linguistic variables	Description	References
Very Good	Perfectly establish open communication atmosphere, effectively communicates and share operational information with other team members using a perfect language	Lamb et al., 2011; Blundel and Ippolito, 2008; Saeed et al., 2016
Good	Sufficiently establish open communication atmosphere, sufficiently communicates and share operational information with other team members using a clear language	
Average	Establish moderate communication atmosphere, moderately communicates and share operational information with other team members using a moderate language clarity	
Bad	Establish ineffective communication atmosphere, communicates and share little operational information with other team members using ineffective language	
Very Bad	Never establish communication atmosphere, never communicates and share operational information and never use proper language	

Table 6.12. Linguistic grades description for teamwork and leadership skills (T&L)

Linguistic variables	Description	References
Very Good	Perfectly plan and confirm the operation with other team members, actively monitor and respect others capabilities and their operational conditions, provide full operational overview to ensure other team members safety, fully respect other team member suggestions and comments, perfectly motivate and appreciate others.	Yule and Brown 2012; Riahi et al., 2013; Sasou and Reason, 1999; Combe and Carrington, 2015
Good	Sufficiently plan and confirm the operation with other team members, sufficiently monitor and respect others capabilities and theiroperational conditions, provide sufficient operational overview to ensure other team members safety, respect other team member sufficiently to their suggestions and comments, sufficiently motivate and appreciate others.	
Average	Plan and confirm the operation fairly enough with other team members, monitor and respect others fairly enough to their capabilities and their operational conditions, provide enough operational overview to ensure other team members safety, respect other team member fairly enough to their suggestions and comments, just enough motivate and appreciate others.	
Bad	Plan and confirm the operation very little with other team members, monitor and respect others very little to their capabilities and their operational conditions, provide little operational overview to ensure other team members safety, respect other team member very little to their suggestions and comments, rarely motivate and appreciate others.	
Very Bad	Never plan and confirm the operation with other team members, never monitor and respect others capabilities and their operational conditions, never provide operational overview to ensure other team members safety, never respect other team member suggestions and comments, never motivate and appreciate others.	

Table 6.13. Linguistic grades description for operator age (OA)

Linguistic variables	Description	References
Very Young	20 – 29 Years	Riahi et al., 2012; Sturman, 2003; Port standard
Young	30 – 39 Years	
Mid Aged	40 – 49 Years	
Old	50 – 59 Years	
Very Old	≥ 60 Years	

Table 6.14. Linguistic grades description for health issue (HI)

Linguistic variables	Description	References
Healthy	Clear from any health problems, mentally very good and perfectly able to concentrate during the operation, following perfect preventive medical care, having excellent sensory and cardiorespiratory function.	Davis et al., 2005; Robertson and Tracy, 1998
Good	Clear from any health problems, mentally good and good to concentrate during the operation, following good preventive medical care, having good sensory and cardiorespiratory function.	
Moderate	Have minor health problems, average in mental condition and average to concentrate during the operation, following average preventive medical care, having average sensory and cardiorespiratory function.	
Bad	Possible to have minor and chronic health problems, bad in mental condition and weak to concentrate during the operation, following low preventive medical care, having low sensory and cardiorespiratory function.	
Severe	Have minor and chronic health problems, unstable mental condition and very weak to concentrate during the operation, not following any preventive medical care, having very low sensory and cardiorespiratory function.	

Table 6.15. Linguistic grades description for body strength (BS)

Linguistic variables	Description	References
Fit	Perfectly cope with the high physical working demand, have excellent work capacity, have excellent mental condition, excellent muscle strength	Wadsworth et al., 2008; Riahi et al., 2013; Smith et al., 2008; Robertson and Tracy, 1998
Good	Sufficiently cope with the high physical working demand, have good work capacity, have good mental condition, good muscle strength	
Moderate	Moderately cope with the high physical working demand, have moderate work capacity, have moderate mental condition, average muscle strength	
Weak	Badly cope with the high physical working demand, have weak work capacity, have weak mental condition, weak muscle strength	
Very Weak	Struggle to cope with the high physical working demand, have very weak work capacity, very weak mental condition, very weak muscle strength	

6.4.2 Mapping process for lower-level MPRIs

In this section, any transformed DoB sets of the given information for each pilot are extracted. The purpose of the mapping process was demonstrated in Section 6.3.5. This section gives a demonstration on how to map the bottom levels of the identified MPRIs to their associated upper levels. This is followed by mapping the aggregated results from the bottom levels of MPRIs towards the main goal. A demonstrative example mapping Pilot 1's MPRIs is given in the following section. All other mapping processes belonging to Pilot 2 and Pilot 3 are presented in Appendix II. For further information, please refer to Appendix II.

6.4.2.1 Working hours (PF-WH)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 1's WH is as follows:

$$\widetilde{WH}_{p1} = \{(V.Good, 0), (Good, 0.3), (Moderate, 0.7), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed on the fuzzy rules in Table (6.16) for mapping pilots' WH to its associated criterion, PF, in order to assess pilot reliability based on WH (Figure 6.4).

Table 6.16. Fuzzy rule base belief structure for PF-WH

Working Hours (WH) to Personal Fatigue (PF)	R^1: if WH assessed 'V. Good', then 100% 'Neutral' R^2: if WH assessed 'Good', then 80% 'S. Fatigued' and 20% 'Neutral' R^3: if WH assessed 'Moderate', then 80% 'Moderate' and 20% 'S. Fatigued' R^4: if WH assessed 'Bad', then 80% 'Fatigued' and 20% 'V. Bad' R^5: if WH assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping WH to PF can be conducted based on given information from Pilot 1 and subject to the fuzzy rules from Table 6.16. They are as follows: Based on R^2 and R^3, the result can transform into 0.06 Neutral ($O^1 = 0.3 \times 0.2$), 0.38 S. Fatigued ($O^2 = (0.3 \times 0.8) + (0.7 \times 0.2)$), and 0.56 Moderate ($O^3 = 0.7 \times 0.8$), respectively. Therefore, the WH for Pilot 1 is assessed as follows:

$$PF - WH_{p1} = \{(Neutral, 0.06), (S.Fatigued, 0.38), (Moderate, 0.56), (Fatigued, 0), (V.Bad, 0)\}$$

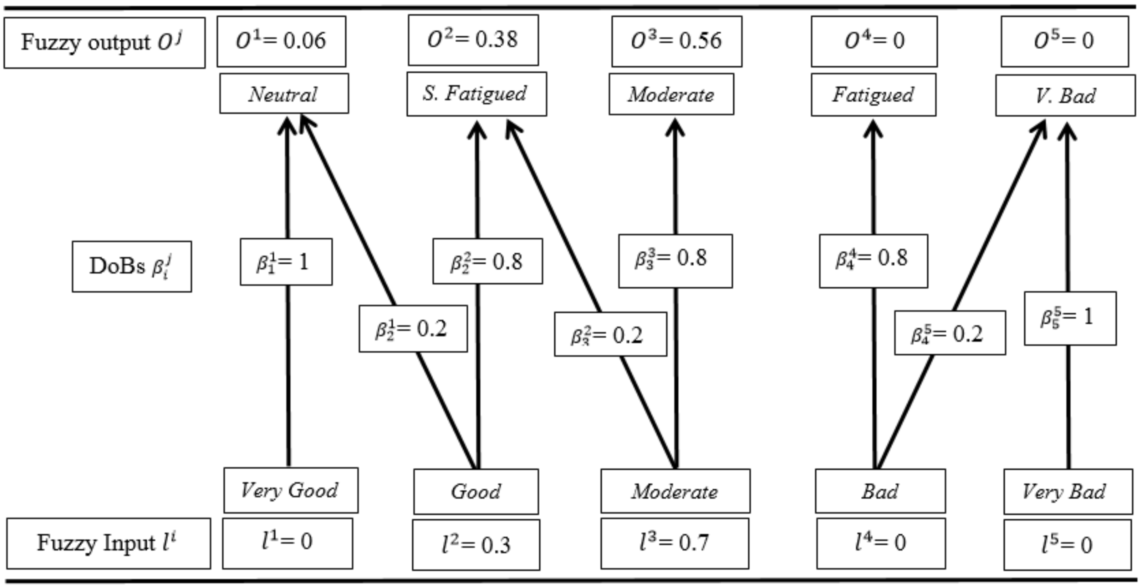

Figure 6.4. Mapping working hours (WH) to personal fatigue (PF)

6.4.2.2 Working stresses (PF-WS)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 1's WS is as follows:

$$\widetilde{WS}_{p1} = \{(V.Low, 0), (Low, 0), (Moderate, 0), (High, 0.7), (V.High, 0.3)\}$$

The harbour masters at this port have agreed on the fuzzy rules from Table (6.17) for mapping pilots' WS to its associated criterion, PF, in order to assess pilot reliability based on WS.

Table 6.17. Fuzzy rule base belief structure for PF-WS

Working Stresses (WS) to Personal Fatigue (PF)	R^1: if WS assessed 'V. Low', then 100% 'Neutral'
	R^2: if WS assessed 'Low', then 90% 'S. Fatigued' and 10% 'Moderate'
	R^3: if WS assessed 'Moderate', then 80% 'Moderate' and 20% 'Fatigued'
	R^4: if WS assessed 'High', then 80% 'Fatigued' and 20% 'V. Bad'
	R^5: if WS assessed 'V. High', then 100% 'V. Bad'

The fuzzy outputs from mapping WS to PF, conducted based on given information for Pilot 1 and subject to fuzzy rules from Table 6.17, are as follows:

Based on R^4 and R^5, the result can transform into 0.56 Fatigued ($O^4 = 0.7 \times 0.8$), and 0.44 V. Bad ($O^5 = (0.7 \times 0.2) + (0.3 \times 1)$), respectively. Therefore, the WS for Pilot 1 is assessed as follows:

$$PF - WS_{p1}$$
$$= \{(Neutral, 0), (S.Fatigued, 0), (Moderate, 0), (Fatigued, 0.56), (V.Bad, 0.44)\}$$

6.4.2.3 Working environment (PF-WEnv)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 1's WEnv is as follows:

$$\widetilde{WEnv}_{p1} = \{(V.Good, 0), (Good, 0.6), (Moderate, 0.4), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules of Table (6.18) for mapping pilots' WEnv to its associated criterion, PF, in order to assess pilot reliability based on WS.

Table 6.18. Fuzzy rule base belief structure for PF-WEnv

Working Environment (WEnv) to Personal Fatigue (PF)	R^1: if WEnv assessed 'V. Good', then 100% 'Neutral' R^2: if WEnv assessed 'Good', then 80% 'S. Fatigued' and 20% 'Moderate' R^3: if WEnv assessed 'Moderate', then 80% 'Moderate' and 20% 'Fatigued' R^4: if WEnv assessed 'Bad', then 80% 'Fatigued' and 20% 'V. Bad' R^5: if WEnv assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping WEnv to PF, conducted based on given information from Pilot 1 and subject to fuzzy rules from Table 6.18, are as follows:

Based on $R^2$and R^3, the result can transform into 0.48 S. Fatigued ($O^2 = 0.6 \times 0.8$), 0.44 Moderate ($O^3 = (0.6 \times 0.2) + (0.4 \times 0.8)$), and 0.08 Fatigued ($O^4 = 0.4 \times 0.2$), respectively. Therefore, the WEnv for Pilot 1 is assessed as follows:

$$PF - WEnv_{p1}$$
$$= \{(Neutral, 0), (S.Fatigued, 0.48), (Moderate, 0.44), (Fatifued, 0.08), (V.Bad, 0)\}$$

6.4.2.4 Decision-making (NTS-DM)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 1's DM is as follows:

$$\widetilde{DM}_{p1} = \{(V.Good, 0.2), (Good, 0.8), (Average, 0), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules from Table (6.19) for mapping pilots' DM to its associated criterion, NTS, in order to assess pilot reliability based on DM.

Table 6.19. Fuzzy rule base belief structure for NTS-DM

Decision Making (DM) to Non-technical Skills (NTS)	R^1: if DM assessed 'V. Good', then 100% 'V. Good'
	R^2: if DM assessed 'Good', then 80% 'Skilful' and 20% 'V. Good'
	R^3: if DM assessed 'Average', then 90% 'Moderate' and 10% 'Bad'
	R^4: if DM assessed 'Bad', then 80% 'Bad' and 20% 'V. Bad'
	R^5: if DM assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping DM to NTS, conducted based on given information from Pilot 1 and subject to fuzzy rules from Table 6.19, are as follows:

Based on $R^1$and R^2, the result can transform into 0.36 V. Good ($O^1 = (0.2 \times 1) + (0.8 \times 0.2)$), and 0.64 Good ($O^2 = 0.8 \times 0.8$), respectively. Therefore, the DM for Pilot 1 is assessed as follows:

$$NTS - DM_{p1} = \{(V.Good, 0.36), (Good, 0.64), (Moderate, 0), (Bad, 0), (V.Bad, 0)\}$$

6.4.2.5 Situation awareness (NTS-SA)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 1's SA is as follows:

$$\widetilde{SA}_{p1} = \{(V.Good, 0), (Good, 0.7), (Average, 0.3), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules in Table (6.20) for mapping pilots' SA to its associated criterion, NTS, in order to assess pilot reliability based on SA.

Table 6.20. Fuzzy rule base belief structure for NTS-SA

Situation Awareness (SA) to Non-technical Skills (NTS)	R^1: if SA assessed ‘V. Good’, then 100% ‘V. Good’ R^2: if SA assessed ‘Good’, then 80% ‘Skilful’ and 20% ‘V .Good’ R^3: if SA assessed ‘Average’, then 90% ‘Moderate’ and 10% ‘Bad’ R^4: if SA assessed ‘Bad’, then 80% ‘Bad’ and 20% ‘V. Bad’ R^5: if SA assessed ‘V. Bad’, then 100% ‘V. Bad’

The fuzzy outputs from mapping SA to NTS, conducted based on given information for Pilot 1 and subject to fuzzy rules from Table 6.20, are as follows:

Based on $R^2$and R^3, the result can transform into 0.14 V. Good ($O^1 = 0.7 \times 0.2$), 0.56 Good ($O^2 = 0.7 \times 0.8$), 0.27 Moderate ($O^3 = 0.3 \times 0.9$), and 0.03 Bad ($O^4 = 0.3 \times 0.1$), respectively. Therefore, the SA for Pilot 1 is assessed as follows:

$$NTS - SA_{p1} = \{(V.Good, 0.14), (Good, 0.56), (Moderate, 0.27), (Bad, 0.03), (V.Bad, 0)\}.$$

6.4.2.6 Communication skills (NTS-CS)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 1’s CS is as follows:

$$\widetilde{CS}_{p1} = \{(V.Good, 0), (Good, 0.7), (Average, 0.3), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules in Table (6.21) for mapping pilots’ CS to its associated criterion, NTS, in order to assess pilot reliability based on CS.

Table 6.21. Fuzzy rule base belief structure for NTS- CS

Communication Skills (CS) to Non-technical Skills (NTS)	R^1: if CS assessed ‘V. Good’, then 100% ‘V. Good’ R^2: if CS assessed ‘Good’, then 80% ‘Skilful’ and 20% ‘V. Good’ R^3: if CS assessed ‘Average’, then 90% ‘Moderate’ and 10% ‘Bad’ R^4: if CS assessed ‘Bad’, then 80% ‘Bad’ and 20% ‘V. Bad’ R^5: if CS assessed ‘V. Bad’, then 100% ‘V. Bad’

The fuzzy outputs from mapping CS to NTS, conducted based on given information for Pilot 1 and subject to fuzzy rules on table 6.21, are as follows:

Based on $R^2$and R^3, the result can transform into 0.14 V. Good ($O^1 = 0.7 \times 0.2$), 0.56 Good ($O^2 = 0.7 \times 0.8$), 0.27 Moderate ($O^3 = 0.3 \times 0.9$), and 0.03 Bad ($O^4 = 0.3 \times 0.1$), respectively. Therefore, the CS for Pilot 1 is assessed as follows:

$$NTS - \mathrm{CS}_{p1} = \{(V.Good, 0.14), (Good, 0.56), (Moderate, 0.27), (Bad, 0.03), (V.Bad, 0)\}$$

6.4.2.7 Teamwork and leadership (NTS-T&L)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 1's T&L is as follows:

$$\widetilde{T\&L}_{p1} = \{(V.Good, 0), (Good, 0), (Average, 0.8), (Bad, 0.2), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules in Table (6.22) for mapping pilots' T&L to its associated criterion, NTS, in order to assess pilot reliability based on T&L.

Table 6.22. Fuzzy rule base belief structure for NTS-T&L

Teamwork and Leadership (T&L) to Non-technical Skills (NTS)	R^1: if T&L assessed 'V. Good', then 100% 'V. Good' R^2: if T&L assessed 'Good', then 80% 'Skilful' and 20% 'V. Good' R^3: if T&L assessed 'Average', then 90% 'Moderate' and 10% 'Bad' R^4: if T&L assessed 'Bad', then 80% 'Bad' and 20% 'V. Bad' R^5: if T&L assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping T&L to NTS, conducted based on given information for Pilot 1 and subject to fuzzy rules on Table 6.22, are as follows:

Based on $R^3$and R^4, the result can transform into 0.72 Moderate ($O^3 = 0.8 \times 0.9$), 0.24 Bad ($O^4 = (0.8 \times 0.1) + (0.2 \times 0.8)$), and 0.04 V. Bad ($O^5 = 0.2 \times 0.2$), respectively. Therefore, the T&L for Pilot 1 is assessed as follows:

$$NTS - T\&L_{p1} = \{(V.Good, 0), (Good, 0), (Moderate, 0.72), (Bad, 0.24), (V.Bad, 0.04)\}$$

6.4.2.8 Health Issues (F&S-HI)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 1's HI is as follows:

$$\widetilde{HI}_{p1} = \{(Healthy, 0.8), (Good, 0.2), (Moderate, 0), (Bad, 0), (Severe, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules in Table (6.23) for mapping pilots' HI to its associated criterion, F&S, in order to assess pilot reliability based on HI.

Table 6.23. Fuzzy rule base belief structure for F&S-HI

Health Issue (HI) to Fitness and Strength (F&S)	R^1: if HI assessed 'Healthy', then 100% 'Fit' R^2: if HI assessed 'Good', then 90% 'Good' and 10% 'Moderate' R^3: if HI assessed 'Moderate', then 90% 'Moderate' and 10% 'Bad' R^4: if HI assessed 'Bad', then 80% 'Bad' and 20% 'Unfit' R^5: if HI assessed 'Severe', then 100% 'Unfit'

The fuzzy outputs from mapping 'HI' to F&S, conducted based on given information for Pilot 1 and subject to fuzzy rules on Table 6.23, are as follows:

Based on R^1 and R^2, the result can transform into 0.8 Fit ($O^1 = 0.8 \times 1$), 0.18 Good ($O^2 = 0.2 \times 0.9$), and 0.02 Moderate ($O^3 = 0.2 \times 0.1$), respectively. Therefore, the HI for Pilot 1 is assessed as follows:

$$F\&S - HI_{p1} = \{(Fit, 0.8), (Good, 0.18), (Moderate, 0.02), (Bad, 0), (Unfit, 0)\}$$

6.4.2.9 Body strength (F&S-BS)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 1's BS is as follows:

$$\widetilde{BS}_{p1} = \{(Fit, 0.8), (Good, 0.2), (Moderate, 0), (Weak, 0), (V.Weak, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules in Table (6.24) for mapping pilots' BS to its associated criterion, F&S, in order to assess pilot reliability based on BS.

Table 6.24. Fuzzy rule base belief structure for F&S-BS

Body Strength (BS) to Fitness and Strength (F&S)	R^1: if BS assessed 'Fit', then 100% 'Fit' R^2: if BS assessed 'Good', then 90% 'Good' and 10% 'Moderate' R^3: if BS assessed 'Moderate', then 90% 'Moderate' and 10% 'Bad' R^4: if BS assessed 'Weak', then 80% 'Bad' and 20% 'Unfit' R^5: if BS assessed 'V. Weak', then 100% 'Unfit'

The fuzzy outputs from mapping BS to F&S, conducted based on given information for Pilot 1 and subject to fuzzy rules in Table 6.24, are as follows:

Based on R^1 and R^2, the result can transform into 0.8 Fit ($O^1 = 0.8 \times 1$), 0.18 Good ($O^2 = 0.2 \times 0.9$), and 0.02 Moderate ($O^3 = 0.2 \times 0.1$), respectively. Therefore, the BS for Pilot 1 is assessed as follows:

$$F\&S - BS_{p1} = \{(Fit, 0.8), (\text{Good}, 0.18), (Moderate, 0.02), (Bad, 0), (Unfit, 0)\}$$

6.4.3 Transforming quantitative data into qualitative

Due to the difficulty of deciding how to assign the degree of belief of a pilot's special training (TP-ST) and age (F&S-OA), a range of assessments was proposed. Based on the experts' opinions, with the support of research conducted by Ramin et al. (2012), the membership function can best be utilised in order to transform the grade of given quantitative data into qualitative.

6.4.3.1 Pilot's qualification and pilotage licensing (TP-QPL)

Based on the previous discussion (Section 6.3.1), harbour masters at this port have assigned the following marks of value to fuzzy rules to evaluate pilot reliability based on the pilot's QPL:

1- If the pilot holds an approved diploma or a BSc in nautical science and an approved pilot licence from the port authority, he will be given 50 per cent. The pilot must satisfy 100 per cent of the port's minimum requirements.

2- If the pilot holds an approved diploma with an approved certificate of competency class 4 (COC IIII) as a 3rd officer, he will be given 60 per cent. Therefore, the pilot is evaluated as 20 per cent at minimum and 80 per cent at second minimum requirement.

3- If the pilot holds an approved diploma with an approved certificate of competency class 3 (COC III) as a 2nd officer or BSc with an approved (COC IIII) as a 3rd officer, then he will be given 70 per cent. Therefore, the pilot is evaluated as 80 per cent at second minimum requirement and 20 per cent on average, which represent the third requirement.

4- If the pilot holds an approved diploma with an approved certificate of competency class 2 (COC II) as a 1st officer or BSc with an approved (COC III) as a 2nd officer, then he will be given 80%. Therefore, the pilot is evaluated as 80 per cent average and 20 per cent second higher requirement.

5- If the pilot holds an approved diploma with an approved certificate of competency class 1 (COC I) as a master mariner or BSc with an approved (COC II) as a 1st officer, then he will be given 90%. Therefore, the pilot is evaluated as 80 per cent second required qualification and 20 per cent uppermost.

6- If the pilot holds an approved BSc with an approved (COC I) as a master mariner, then he will be given 100%. Therefore, the pilot is evaluated as 100 per cent the uppermost requirement.

According to the given pilots' information, with reference to the above rules, Pilot 1's TP-QPL is assessed based on his QPL as follows:

$$\widetilde{QPL}_{p1} = \{(Uppermost, 0.2), (Second\ Higher, 0.8), (Average, 0), (Second\ Min., 0), (Minimum.,0)\}$$

The harbour masters at this port have agreed to the fuzzy rules in Table (6.25) for mapping pilots' QPL to its associated criterion, TP, in order to assess pilot reliability based on QPL.

Table 6.25. Fuzzy rule base belief structure for TP-QPL

Qualification and pilotage licensing (QPL) to Technical Proficiency (TP)	R^1: if QPL assessed 'Uppermost', then 100% 'V. Good' R^2: if QPL assessed '2nd Higher', then 80% 'Good' and 20% 'V. Good' R^3: if QPL assessed 'Average', then 80% 'Average' and 20% 'Good' R^4: if QPL assessed '2nd Min.', then 90% 'Low' and 10% 'Average' R^5: if QPL assessed 'Min', then 100% 'Basic'

The fuzzy outputs from mapping QPL to TP, conducted based on given information for Pilot 1 and subject to fuzzy rules in Table 6.25, are as follow:

Based on R^1 and R^2, the result can transform into 0.36 V. Good ($O^1 = (0.2 \times 1) + (0.8 \times 0.2)$), and 0.64 Good ($O^2 = 0.8 \times 0.8$), respectively. Therefore, the QPL for Pilot 1 is assessed as follows:

$$TP - QPL_{p1} = \{(V.Good, 0.36), (Good, 0.64), (Average, 0), (Low, 0), (Basic, 0)\}$$

6.4.3.2 Pilot's special training (TP-ST)

Similar to the requirements of pilot qualifications required by the port authority, there are sets of minimum basic training courses that are also essential for a pilot to be endorsed. According to the port authority requirements, the following are compulsory basic training courses that a pilot must have when applying for a pilotage licence:

1- Proficiency in Survival Craft (PSC);

2- Personal Survival Technique (PST);

3- Fire Prevention and Firefighting (FPF);
4- Elementary First Aid (EFA);
5- Advanced Fire Prevention and Firefighting (AFF).

The authority also recommends some extra training courses, but they are optional. These extra courses are:

1- Global Maritime Distress and Safety System (GMDSS) training;
2- Radar simulation training;
3- Advanced Pilot Training (APT) course;
4- Bridge Resource Management (BRM) training course;
5- Port State Control (PSC) training;
6- Ship-handling simulator.

According to the experts' opinions, having valid course certificates for more than nine courses makes one a 'well-trained' pilot. This information helps in developing the membership function used to evaluate pilots based on their ST. Accordingly, if the pilot holds one of these certificates, then 10 per cent will be given for each valid certificate; if the certificate is not valid, then 0 per cent is given. Based on the pilot's given information in the test case, the following are the training courses that Pilot 1 has:

1- Proficiency in survival craft (PSC) (Valid);
2- Personal survival technique (PST) (Valid);
3- Fire prevention and firefighting (FPFF) (Valid);
4- Elementary first aid (EFA) (not valid);
5- Advanced fire prevention and firefighting certificate (AFF) (Valid);
6- Ship-handling simulator certificate (not valid);

7- Global Maritime Distress and Safety System (GMDSS) certificate (Valid);

8- Advanced Pilot Training (APT) certificate (Valid);

9- Bridge Resource Management (BRM) training course (Valid).

Based on the pilot’s stated valid training certificates, 70 per cent is given to Pilot 1. The membership function model constructed is shown in Figure (6.5).

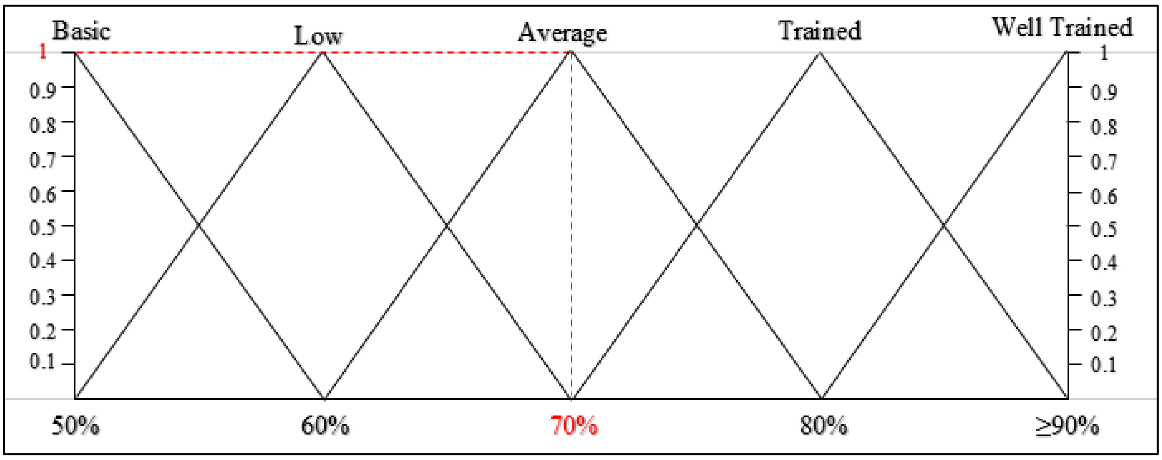

Figure 6.5. The membership function for Pilot 1's special training (TP-ST)

The horizontal axis represents the quantitative number, while the vertical axis represents the belief degrees. When a given quantitative number is found not ranging between two different grades, then 100 per cent will be given. According to the given pilot's information, with reference to the above information, Pilot 1's TP-ST is assessed based on his ST as follows:

$$\widetilde{ST}_{\mathrm{p1}} = \{(Well\,Trained, 0), (Trained, 0), (Average, 1), (Low, 0), (Basic, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules in Table (6.26) for mapping pilots’ ST to its associated criterion, TP, in order to assess pilot reliability based on ST.

Table 6.26. Fuzzy rule base belief structure for TP-ST

Special Training (ST) to Technical Proficiency (TP)	R^1: if ST assessed 'Well Trained', then 100% 'V. Good'
	R^2: if ST assessed 'Trained', then 80% 'Good' and 20% 'V. Good'
	R^3: if ST assessed 'Average', then 80% 'Average' and 20% 'Good'
	R^4: if ST assessed 'Low', then 80% 'Low' and 20% 'Average'
	R^5: if ST assessed 'Basic', then 100% 'Basic'

The fuzzy outputs from mapping ST to TP, conducted based on given information for Pilot 1 and subject to fuzzy rules in Table 6.26, are as follows:

Based on R^3 the result can transform into 0.20 Good ($O^2 = 0.2 \times 1$), and 0.80 Average ($O^3 = 1 \times 0.8$), respectively. Therefore, the ST for Pilot 1 is assessed as follows:

$$TP - ST_{p1} = \{(V.Good, 0), (Good, 0.20), (Average, 0.80), (Low, 0), (Basic, 0)\}$$

6.4.3.3 Pilot's working experience (TP-WEx)

According to the given pilots' information, a membership function model can be constructed based on the number of years served as a pilot, as shown in Figure (6.6).

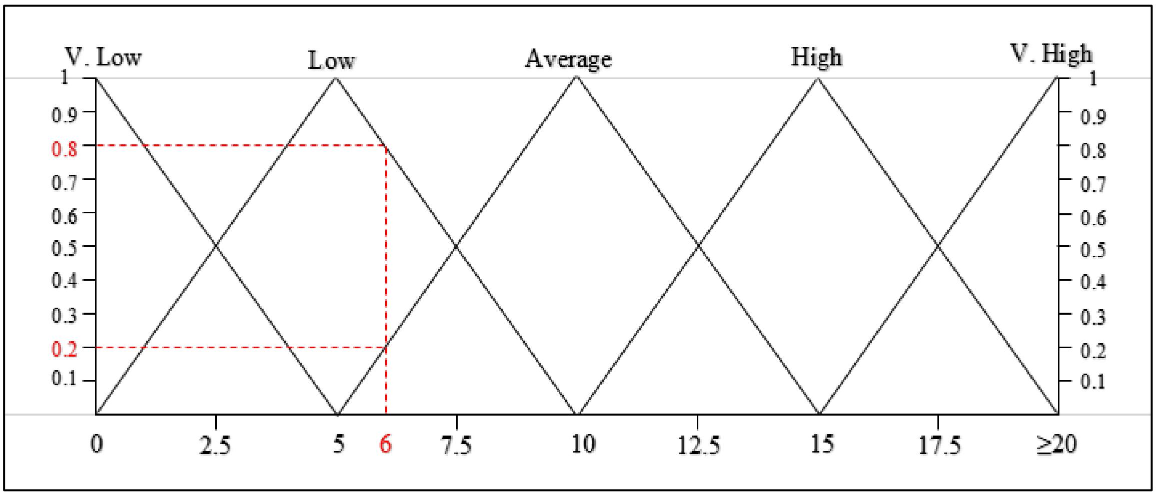

Figure 6.6. The membership function for Pilot 1's working experience (TP-WEx)

The horizontal axis represents the quantitative number, while the vertical axis represents the belief degrees. When a given quantitative number is found in the range of $h_{n+1,i}$(with a grade H_{n+1}) and $h_{n,i}$(with a grade H_n), the belief degree can be calculated using the following formulas:

$\beta_{n,i} = \frac{h_{n+1,i} - h_i}{h_{n+1,i} - h_{n,i}}$, if $h_{n,i} < h_i < h_{n+1,i}$

$\beta_{n+1,i} = 1 - \beta_{n,i}$

Where, $\beta_{n,i}$ is the degree of belief of the given quantitative number with the grade H_{n+1}. Based on the given information from Pilot 1, the degree of belief for Pilot's 1 TP-WEx can be calculated as follows:

1- H_{n+1} is the 'Average' grade.

2- H_n is the 'Low' grade.

3- h_i= 6, $h_{n,i}$= 5, and $h_{n+1,i}$= 10.

4- $\beta_{n,i}$ = (10-6)/(10-5) = 0.8 with the 'Low' grade, and $\beta_{n+1,i}$ = 1-0.8 = 0.2 with the 'Average' grade.

Therefore, the assessment of Pilot 1's TP-WExs is as follows:

$$\widetilde{WEx}_{p1} = \{(V.High, 0), (High, 0), (Average, 0.2), (Low, 0.8), (V.Low, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (6.27) for mapping pilots' WEx to its associated criterion, TP, in order to assess pilot reliability based on WEx.

Table 6.27. Fuzzy rule base belief structure for TP-WEx

Working Experience (WEx) to Technical Proficiency (TP)	R^1: if WEx assessed 'Very High', then 100% 'V. Good' R^2: if WEx assessed 'High', then 80% 'Good' and 20% 'V. Good' R^3: if WEx assessed 'Average', then 80% 'Average' and 20% 'Good' R^4: if WEx assessed 'Low', then 90% 'Low' and 10% 'Average' R^5: if WEx assessed 'V. Low', then 100% 'Basic'

The fuzzy outputs from mapping WEx to TP, conducted based on given information for Pilot 1 and subject to fuzzy rules on Table 6.27, are as follows:

Based on R^3 and R^4 the result can transform into 0.04 Good ($O^2 = 0.2 \times 0.2$), 0.24 Average ($O^3 = (0.2 \times 0.8) + (0.8 \times 0.1)$), and 0.72 Low ($O^4 = 0.8 \times 0.9$) respectively. Therefore, the WEx for Pilot 1 is assessed as follows:

$$TP - WEx_{p1} = \{(V.\text{Good}, 0), (\text{Good}, 0.04), (Average, 0.24), (Low, 0.72), (Basic, 0)\}$$

6.4.3.4 Pilot’s age

Due to the difficulty of how to assign a degree of belief to a pilot’s age, a range of assessments were proposed. Based on the experts’ opinions, that the membership function can be utilised in order to transform the grade for given quantitative data into a qualitative degree of beliefs, with reference to a study conducted by Riahi et al. (2012), the following rules were used:

1- If the pilot is 60 years old, he is considered ‘Very old’.
2- If the pilot is 50 years old, he is considered ‘Old’.
3- If the pilot is 40 years old, he is considered ‘Mid-Aged’.
4- If the pilot is 30 years old, he is considered ‘Young’.
5- If the pilot is 20 years old, he is considered ‘Very Young’.

Based on the information from each pilot, the membership function on Figure (6.7) represents the assessment F&S-OA of Pilot 1.

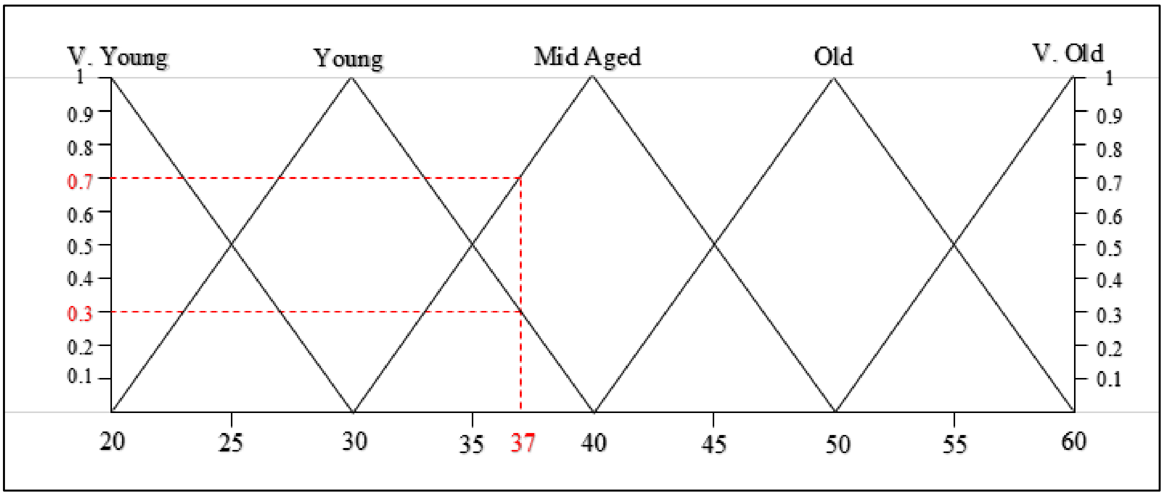

Figure 6.7. The membership function for Pilot 1's age (F&S-OA)

The horizontal axis represents the quantitative number, while the vertical axis represents the belief degrees. When a given quantitative number is found in the range of $h_{n+1,i}$(with a grade H_{n+1}) and $h_{n,i}$(with a grade H_n), the belief degree can be calculated using the following formulas:

$\beta_{n,i} = \frac{h_{n+1,i}-h_i}{h_{n+1,i}-h_{n,i}}$, if $h_{n,i} < h_i < h_{n+1,i}$

$\beta_{n+1,i} = 1 - \beta_{n,i}$

Where, $\beta_{n,i}$ is the degree of belief of the given quantitative number with the grade H_{n+1}. Based on the given information from Pilot 1, the degree of belief for Pilot 1's F&S-OA can be calculated as follows:

1- H_{n+1} is the ‘Mid Aged’ grade.
2- H_n is the ‘Young’ grade.
3- h_i= 37, $h_{n,i}$= 30, and $h_{n+1,i}$= 40.
4- $\beta_{n,i}$ = (40-37)/(40-30) = 0.3 with the ‘Young’ grade, and $\beta_{n+1,i}$ = 1-0.3 = 0.7 with the ‘Mid Aged’ grade.

Therefore, the assessment of Pilot 1's F&S-OA based on their information is as follows:

$\widetilde{OA}_{\mathrm{p1}} = \{(Very\ Young, 0), (Young, 0.3), (Mid\ Aged, 0.7), (Old, 0), (Very\ Old, 0)\}$

The harbour masters at this port have agreed to the fuzzy rules in Table (6.28) for mapping pilots’ OA to its associated criterion, F&S, in order to assess pilot reliability based on OA.

Table 6.28. Fuzzy rule base belief structure for F&S-OA

Operator Age (OA) to Fitness & Strength (F&S)	R^1: if OA assessed ‘Very Young’, then 100% ‘Fit’ R^2: if OA assessed ‘Young’, then 80% ‘Good’ and 20% ‘Fit’ R^3: if OA assessed ‘Mid Aged’, then 90% ‘Moderate’ and 10% ‘Bad’ R^4: if OA assessed ‘Old’, then 80% ‘Bad’ and 20% ‘Unfit’ R^5: if OA assessed ‘Very Old’, then 100% ‘Unfit’

The fuzzy outputs from mapping OA to F&S, , conducted based on given information for Pilot 1 and subject to fuzzy rules in Table 6.28, are as follows:

Based on $R^2$and R^3 the result can transform into 0.06 Fit ($O^1 = 0.3 \times 0.2$), 0.24 Good ($O^2 = 0.3 \times 0.8$), 0.63 Moderate ($O^3 = 0.7 \times 0.9$), and 0.07 Bad ($O^4 = 0.7 \times 0.1$) respectively. Therefore, the OA for Pilot 1 is assessed as follows:

$$F\&S - OA_{p1}$$
$$= \{(Fit, 0.06), (Good, 0.24), (Moderate, 0.63), (Bad, 0.07), (Unfit, 0)\}$$

6.4.4 Mapping main criteria to goal

Following the aggregation process of all sub-criteria to their associated criterion, the main criterion can be further mapped similarly as above. The aggregation process of all sub-criteria is presented in Appendix II. Accordingly, the aggregated main criterion for Pilot 1 is as follows:

$$\widetilde{TP}_{\mathrm{p1}} = \{(Excellent, 0.02), (Professional, 0.1), (Average, 0.37), (Low, 0.52), (Basic, 0)\}$$

$$\widetilde{PF}_{\mathrm{p1}} = \{(Neutral, 0.01), (S.Fatigued, 0.29), (Moderate, 0.31), (Fatigued, 0.24), (V.\mathrm{Bad}, 0.15)\}$$

$$\widetilde{NTS}_{\mathrm{p1}} = \{(Excellent, 0.05), (Skillful, 0.19), (Moderate, 0.57), (Bad, 0.16), (Unskilful, 0.02)\}$$

$$\widetilde{F\&S}_{\mathrm{p1}} = \{(V.Good, 0.82), (Fit, 0.15), (Moderate\ Fit, 0.03), (Bad, 0), (Unfit, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules in Table (6.29) for mapping

Pilot 1 main criteria (TP, PF, NTS, and F&S) to the main goal, Pilot Reliability (PR).

Table 6.29. Fuzzy rule base belief structure for Main criteria to PR

Technical Proficiency (TP) to Main Goal (PR)	R^1: if TP assessed ‘V. Good’, then 100% ‘Very High’ R^2: if TP assessed ‘Good’, then 80% ‘High’ and 20% ‘Very High’ R^3: if TP assessed ‘Average’, then 80% ‘Moderate’ and 20% ‘High’ R^4: if TP assessed ‘Low’, then 80% ‘Low’ and 20% ‘Very Low’ R^5: if TP assessed ‘Basic’, then 100% ‘Very Low’
Personal Fatigue (PF) to Main Goal (PR)	R^1: if TP assessed ‘Neutral, then 100% ‘Very High’ R^2: if TP assessed ‘S. Fatigued’, then 80% ‘High’ and 20% ‘Very High’ R^3: if TP assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘High’ R^4: if TP assessed ‘Fatigued’, then 80% ‘Low’ and 20% ‘Very Low’ R^5: if TP assessed ‘Very Bad’, then 100% ‘Very Low’
Non-Technical Skills (NTS) to Main Goal (PR)	R^1: if TP assessed ‘V. Good’, then 100% ‘Very High’ R^2: if TP assessed ‘Good’, then 80% ‘High’ and 20% ‘Very High’ R^3: if TP assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘High’ R^4: if TP assessed ‘Bad’, then 80% ‘Low’ and 20% ‘Very Low’ R^5: if TP assessed ‘V. Bad’, then 100% ‘Very Low’
Fitness & Strength (F&S) to Main Goal (PR)	R^1: if TP assessed ‘Fit’, then 100% ‘Very High’ R^2: if TP assessed ‘Good’, then 80% ‘High’ and 20% ‘V. High’ R^3: if TP assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘High’ R^4: if TP assessed ‘Bad’, then 80% ‘Low’ and 20% ‘Very Low’ R^5: if TP assessed ‘Unfit’, then 100% ‘Very Low’

Accordingly, the results obtained from the mapping process for Pilot 1 are as follows:

$$PRTP_{p1} = \{(V.High, 0.03), (High, 0.12), (Moderate, 0.33), (Low, 0.41), (V.Low, 0.10)\}$$

$$PRPF_{p1} = \{(V.High, 0.07), (High, 0.26), (Moderate, 0.28), (Low, 0.19), (V.Low, 0.20)\}$$

$$PRNTS_{p1} = \{(V.High, 0.09), (High, 0.21), (Moderate, 0.52), (Low, 0.13), (V.Low, 0.06)\}$$

$$PRF\&S_{p1} = \{(V.High, 0.85), (High, 0.13), (Moderate, 0.03), (Low, 0), (V.Low, 0)\}$$

6.4.5 Weight assignment for each MPRI

The degree of importance plays an important role in the assessment when using the ER approach. The criteria of MPRIs can be weighted using any of the techniques capable of determining the degree of importance of the criterion used for assessment. Local weights, which reflect the degree of importance of each criterion with its associated upper-level criterion, can be obtained using one of the weighting techniques, such as a simple rating method or pairwise comparisons (Yang and Xu, 2002). One of the most commonly used methods capable of addressing the local weight of each criterion is the AHP, which was introduced by Saaty (1980). The AHP employs a unidirectional hierarchal relationship of the linear top-down form in the hierarchy, showing the degree of the relationship from the goal up to the bottom level in the hierarchy (Saaty, 1990). The ANP method is a non-linear approach used to identify the interdependencies among the criteria. It is also capable of determining the weight of each criterion in the more complicated interrelationships among them. The characteristics and calculations of the AHP and ANP were described in Chapters 4 and 5, respectively. For further detail, please refer to chapters 4 and 5. The weights identified by these two methods are shown in Table 6.30.

Table 6.30. Weight assignment and ranking

Goal	**Sub-level**	**MPRIs**	**AHP**			**ANP**		
			LW	**GW**	**Ranking**	**GW**	**NW**	**Ranking**
Pilot Reliability	**TP** (0.045)	**QPL**	0.183	0.021	11	0.004	0.089	13
		ST	0.452	0.052	6	0.013	0.289	11
		WEx	0.365	0.042	9	0.028	0.622	10
	PF (0.186)	**WH**	0.113	0.050	8	0.039	0.210	9
		WS	0.547	0.243	1	0.068	0.366	6
		WEnv	0.340	0.151	2	0.079	0.424	5
	NTS (0.606)	**DM**	0.074	0.027	10	0.045	0.075	8
		SA	0.169	0.062	5	0.094	0.155	3
		CS	0.400	0.146	3	0.142	0.234	2
		T&L	0.357	0.130	4	0.325	0.536	1
	F&S (0.163)	**OA**	0.111	0.008	13	0.008	0.049	12
		HI	0.204	0.015	12	0.091	0.558	4
		BS	0.685	0.051	7	0.064	0.393	7

((**TP**: Technical Proficiency; **QPL**: Qualification and Pilotage Licencing; **ST**: Special Training: **WEx**: Working Experience), (**PF**: Personal Fatigue; **WH**: Working Hours; **WS**: Work Stresses; **WEnv**: Working Environment), (**NTS**: Non-Technical Skills; **DM**: Decision-Making; **SA**: Situation Awareness; **CS**: Communication Skills; **T&L**: Teamwork and Leadership), (**F&S**: Fitness & Strength; **OA**: Operator Age; **HI**: Health Issue; **BS**: Body Strength)).

6.4.6 Fuzzy set aggregation process

The aggregation process is an essential process that helps to aggregate criteria to their associated upper criterion. This process is as essential part of the reliability evaluation and can be done with the help of the algorithms of ER. Based on the above mapping process for Pilot 1, the following section shows the synthesis of Pilot 1's personal fatigue sub-criterion using the ER algorithms, followed by the synthesising of the basic criteria in the hierarchal structure. This is done using a multi-criteria assessor software called an Intelligent Decision-Making Software (IDS), which was chosen due to its ease of use and its accessibility within the industry and academic research. The full aggregation process is presented in Appendix II. Please refer to Appendix II for the full explanation of all pilots.

6.4.6.1 Evaluation of the pilot's personal fatigue criterion (PF)

The following is an example of how to aggregate three sets of information using the ER algorithms. Using ER equations, the aggregation process for personal fatigue (PF), in relation to the sub-criteria of working hours (WH), work stresses (WS), and working Environment (WEnv) and based on the information given by Pilot 1, is as follows:

To aggregate the personal fatigue ($\widetilde{PF}$) Sub-Criteria $\widetilde{\mathrm{PF}}_{\mathrm{WH}}$, $\widetilde{\mathrm{PF}}_{\mathrm{WS}}$, and $\widetilde{\mathrm{PF}}_{\mathrm{WEnv}}$ using ER algorithms, we need to define the following:

$\widetilde{\mathrm{PF}}_{\mathrm{WH}}$, which represents the sub-criterion Working Hours (WH);

$\widetilde{\mathrm{PF}}_{\mathrm{WS}}$, which represents the sub-criterion Work Stresses (WS);

$\widetilde{\mathrm{PF}}_{\mathrm{WEnv}}$, which represents the sub-criterion Working Environment (WEnv).

Based on the given fuzzy information of WH,WS, and WEnv for Pilot 1, the aggregation process is as follows:

$R\widetilde{\mathrm{PF}}_{\mathrm{WH}}$ = {(Neutral, 0.06), (S. Fatigued, 0.38), (Moderate, 0.56), (Fatigued, 0),(V. Bad, 0)}

$R\widetilde{\mathrm{PF}}_{\mathrm{WS}}$ = {(Neutral, 0), (S. Fatigued, 0), (Moderate, 0), (Fatigued, 0.56), (V. Bad, 0.44)}

$R\widetilde{\mathrm{PF}}_{\mathrm{WS}}$ = {(Neutral, 0), (S. Fatigued, 0.48), (Moderate, 0.44), (Fatigued, 0.08), (V. Bad, 0)}

Weight has been given to each criterion using the AHP and ANP; the AHP gives the local weight, while the ANP gives the global weight. The global weight is then normalised and used in this section. In addition, the result using the AHP weight is obtained to compare the results. Accordingly, the global weights obtained by ANP are as follows:

ω_{WH}= 0.039, ω_{WS}= 0.068, and ω_{WEnv}= 0.079

Where:

ω_{WH}, is the global weight assigned for PF-WH;

ω_{WS}, is the global weight assigned for PF-WS;

ω_{WEnv}, represents the global weight assigned for PF-WEnv.

Since the weights' sums are not equal to 1, they must be normalised. To normalise the weight for each criterion, divide the weight of each criterion by the sum of all criteria. In our example, the sum of WH, WS, and WEnv are as follows:

$\omega_{WH} + \omega_{WS} + \omega_{WEnv}$ = 0.039 + 0.068 + 0.079 = 0.186.

A normalised ω_{WH}= 0.039/0.186= 0.21.

Similarly, ω_{WS}= 0.37 and ω_{WEnv}= 0.42

When aggregating more than three criteria, we need to aggregate the first two criteria, followed by aggregating the result from the first two with the third, and so forth. The following is the aggregating process of the first two sub-criteria of PF, $\widetilde{PF}_{WH}$, and $\widetilde{PF}_{WS}$. M_1^m represents the subset$\widetilde{PF}_{WH}$, and M_2^m represents the subset $\widetilde{PF}_{WS}$. Using ER equation (6.6) can obtain the following:

$M_1^m = \omega_{WH}\beta_1^m$, where ($m$ = 1,2,3,4,5)

$M_2^m = \omega_{WS}\beta_2^m$, where ($m$ = 1,2,3,4,5)

As a result, the following table is constructed:

When, m= 1, M_1^1= 0.21×0.06 = 0.01, M_2^1= 0.37×0= 0

m= 2, M_1^2= 0.21×0.38 = 0.08, M_2^2= 0.37×0= 0

m= 3, M_1^3= 0.21×0.56= 0.12, M_2^3= 0.37×0= 0

m= 4, M_1^4= 0.21×0= 0, M_2^4= 0.37× 0.18= 0.20

m= 5, M_1^5= 0.21×0= 0, M_2^5= 0.37× 0.82= 0.16

When M_{H_1} represents the individual remaining belief for $\mathrm{M}_1^{\mathrm{m}}$, and M_{H_2} represents the individual remaining belief for $\mathrm{M}_2^{\mathrm{m}}$; therefore, equation (6.7) can be applied as follows:

- $M_{H_{WH}} = \bar{M}_{H_{WH}} + \widetilde{M}_{H_{WH}}$
- $M_{H_{WS}} = \bar{M}_{H_{WS}} + \widetilde{M}_{H_{WS}}$

$\bar{M}_{H_{WH}}, \widetilde{M}_{H_{WH}}$, and $\bar{M}_{H_{WS}}\widetilde{M}_{H_{WS}}$ can be found by applying equations (6.8-6.9) as follows:

- $\bar{M}_{H_{WH}} = 1 - \omega_{WH}$ =1- 0.21 = 0.790
- $\bar{M}_{H_{WS}} = 1 - \omega_{WS}$ =1- 0.37 = 0.634
- $\widetilde{M}_{H_{WH}} = \omega_{WH}(1 - \sum_{m}^{5} \beta_1^m)$ = 0.21× (1- (0.06+0.38+0.56+0+0)) = 0
- $\widetilde{M}_{H_{WS}} = \omega_{WS}(1 - \sum_{m}^{5} \beta_2^m)$ = 0.37× (1- (0+0+0+0.56+0.44)) = 0
- $M_{H_{WH}} = \bar{M}_{H_{WH}} + \widetilde{M}_{H_{WH}}$ = 0.790+0= 0.790
- $M_{H_{WS}} = \bar{M}_{H_{WS}} + \widetilde{M}_{H_{WS}}$ = 0.634+0= 0.634

By using equations (6.10-6.13) to find $\beta^{m'} = k\left(M_1^m M_2^m + M_1^m M_{H_{WS}} + M_2^m M_{H_{WH}}\right)^{-1}$, $(\bar{M}'_{H_U})$, and $(\widetilde{M}'_{H_U})$, we need to find k using equation (6.13):

$k = [1 - \sum_{T=1}^{5} \sum_{R=1 \neq T}^{5} M_1^T M_2^R]^{-1}$

$$k = \begin{pmatrix} & -+ & M_1^1 M_2^2 + & M_1^1 M_2^3 + & M_1^1 M_2^4 + & M_1^1 M_2^5 + \\ & M_1^2 M_2^1 + & -+ & M_1^2 M_2^3 + & M_1^2 M_2^4 + & M_1^2 M_2^5 + \\ 1 - & M_1^3 M_2^1 + & M_1^3 M_2^2 + & -+ & M_1^3 M_2^4 + & M_1^3 M_2^5 + \\ & M_1^4 M_2^1 + & M_1^4 M_2^2 + & M_1^4 M_2^3 + & -+ & M_1^4 M_2^5 + \\ & M_1^5 M_2^1 + & M_1^5 M_2^2 + & M_1^5 M_2^3 + & M_1^5 M_2^4 + & - \end{pmatrix}^{-1}$$

$$\begin{aligned} k = \quad & \big(1 - (- + (0.013 \times 0) + (0.013 \times 0) + (0.013 \times 0.205) + (0.013 \times 0.161) + \\ & (0.08 \times 0) + - + (0.08 \times 0) + (0.08 \times 0.205) + (0.08 \times 0.161) + (0.117 \times 0) + \\ & (0.117 \times 0) + - + (0.117 \times 0.205) + (0.117 \times 0.161) + (0 \times 0) + (0 \times 0) + (0 \times \\ & 0) + - + (0 \times 0.161) + (0 \times 0) + (0 \times 0) + (0 \times 0) + (0 \times 0.205) + -)\big)^{-1} \end{aligned}$$

$$k = \begin{pmatrix} & -+ & 0+ & 0+ & 0.003+ & 0.002+ \\ & 0+ & -+ & 0+ & 0.016+ & 0.013+ \\ 1 - & 0+ & 0+ & -+ & 0.024+ & 0.019+ \\ & 0+ & 0+ & 0+ & -+ & 0+ \\ & 0+ & 0+ & 0+ & 0+ & - \end{pmatrix}^{-1}$$

k= 1.08

Then, before using equations (6.13-6.15) to find (β^{m}) and (M_{H_U}), we need to utilise equations (6.11-6.12) to find ($\beta^{m'}$), ($\bar{M}'_{H_U}$), and ($\tilde{M}'_{H_U}$), as follows:

$\bar{M}'_{H_U} = K(\bar{M}_{H_{WH}}\bar{M}_{H_{WS}})$ = 1.08× 0.79× 0.63= 0.53

$\tilde{M}'_{H_U} = K(\tilde{M}_{H_{WH}}\tilde{M}_{H_{WS}} + \tilde{M}_{WH}\bar{M}_{H_{WS}} + \bar{M}_{H_{WH}}\tilde{M}_{H_{WS}})$ =

1.08×[(0×0)+(0.79×0)+(0×0.63)]=0

Accordingly, when $\beta^{m} = \frac{\beta^{m'}}{(1-\bar{H}_U)}\ , where\ (m = 1{,}2{,}3{,}4{,}5)$, then:

$\beta^{m'} = k\left(M_1^m M_2^m + M_1^m M_{H_{WS}} + M_2^m M_{H_{WH}}\right)$

$\beta^{1'} = k\left(M_1^1 M_2^1 + M_1^1 M_{H_{WS}} + M_2^1 M_{H_{WH}}\right)$ = 1.08 × [(0.01×0)+(0.01×0.63)+(0.79×0)]= 0.01

$\beta^{2'} = k\left(M_1^2 M_2^2 + M_1^2 M_{H_{WS}} + M_2^2 M_{H_{WH}}\right)$ = 1.08 × [(0.08×0)+(0.08×0.63)+(0.79×0)] = 0.06

$\beta^{3'} = k\left(M_1^3 M_2^3 + M_1^3 M_{H_{WS}} + M_2^3 M_{H_{WH}}\right)$ = 1.08 × [(0.12×0)+(0.12×0.63)+(0.79×0)] = 0.08

$\beta^{4'} = k\left(M_1^4 M_2^4 + M_1^4 M_{H_{WS}} + M_2^4 M_{H_{WH}}\right)$ = 1.08 × [(0×0.21)+(0×0.63)+(0.79×0.21)]= 0.18

$\beta^{5'} = k\left(M_1^5 M_2^5 + M_1^5 M_{H_{WS}} + M_2^5 M_{H_{WH}}\right)$ = 1.08 × [(0×0.16)+(0×0.63)+(0.79×0.16)]= 0.14

From the above aggregations, the obtained results $\beta^{1'}$, $\beta^{2'}$,$\beta^{3'}$,$\beta^{4'}$, and $\beta^{5'}$represent M_{12}^1, M_{12}^2, M_{12}^3, M_{12}^4, and $M_{12}^5$for the first two aggregations. These will be used with the third aggregation similar to the above aggregation process. The following are the aggregation of the criterion WEnv with the aggregated result from WH and WS:

M_{12}^m represents the aggregated subset of $\widetilde{PF}_{WH}$, and $\widetilde{PF}_{WS}$, while M_3^m represents the subset $\widetilde{PF}_{WEnv}$. Using the ER equation (6.6) can obtain the following:

$M_3^m = \omega_{WEnv}\beta_3^m$, where ($m$ = 1,2,3,4,5)

When, m= 1, M_{12}^1= 0.01, M_3^1= 0.42×0= 0

m= 2, M_{12}^2= 0.06, M_3^2= 0.42×0.48= 0.20

m= 3, M_{12}^3= 0.08, M_3^3= 0.42×0.44= 0.19

m= 4, M_{12}^4= 0.18, M_3^4= 0.42×0.08= 0.03

m= 5, M_{12}^5= 0.14, M_3^5= 0.42×0= 0

When $M_{H_{12}}$ represents the individual remaining belief for $\mathrm{M}_{12}^{\mathrm{m}}$, and M_{H_3} represents the individual remaining belief for $\mathrm{M}_3^{\mathrm{m}}$, equation 6.7 can be applied as follows:

- $M_{H_{WEnv}} = \bar{M}_{H_{WEnv}} + \widetilde{M}_{H_{WEnv}}$

$\bar{M}_{H_{WEnv}}, \widetilde{M}_{H_{WEnv}}$ can be found by applying equations (6.8-6.9) as follows:

- $\bar{M}_{H_{WEnv}} = 1 - \omega_{WEnv}$ = 1- 0.42= 0.58
- $\widetilde{M}_{H_{WEnv}} = \omega_{WEnv}(1 - \sum_m^5 \beta_3^m)$ = 0.42× (1- (0+0.48+0.44+0.08+0))= 0
- $M_{H_{WEnv}} = \bar{M}_{H_{WEnv}} + \widetilde{M}_{H_{WEnv}}$ = 0.58+0= 0.58

By using equations (6.10-6.13) to find $\beta^{m'} = k\left(M_{12}^m M_3^m + M_{12}^m M_{H_{WEnv}} + M_3^m M_{H_{12}}\right)^{-1}$, ($\bar{M}'_{H_U}$), and ($\widetilde{M}'_{H_U}$), we find k using equation (6.13):

$k = [1 - \sum_{T=1}^5 \sum_{R=1 \neq T}^5 M_{12}^T M_3^R]^{-1}$

$$k = \begin{pmatrix} & -+ & M_{12}^1M_3^2+ & M_{12}^1M_3^3+ & M_{12}^1M_3^4+ & M_{12}^1M_3^5+ \\ & M_{12}^2M_3^1+ & -+ & M_{12}^2M_3^3+ & M_{12}^2M_3^4+ & M_{12}^2M_3^5+ \\ 1- & M_{12}^3M_3^1+ & M_{12}^3M_3^2+ & -+ & M_{12}^3M_3^4+ & M_{12}^3M_3^5+ \\ & M_{12}^4M_3^1+ & M_{12}^4M_3^2+ & M_{12}^4M_3^3+ & -+ & M_{12}^4M_3^5+ \\ & M_{12}^5M_3^1+ & M_{12}^5M_3^2+ & M_{12}^5M_3^3+ & M_{12}^5M_3^4+ & - \end{pmatrix}^{-1}$$

$k =$ $\big(1 - (- + (0.01 \times 0.20) + (0.01 \times 0.19) + (0.01 \times 0.03) + (0.01 \times 0) +$ $(0.06 \times 0) + - + (0.06 \times 0.19) + (0.06 \times 0.03) + (0.06 \times 0) + (0.08 \times 0) + (0.08 \times$ $0.20) + - + (0.08 \times 0.03) + (0.08 \times 0) + (0.18 \times 0) + (0.18 \times 0.20) + (0.18 \times$

$0.19) + - + (0.18 \times 0) + (0.14 \times 0) + (0.14 \times 0.20) + (0.14 \times 0.19) + (0.14 \times$

$0.03) + -)\big)^{-1}$

$$k = \left(1 - \begin{matrix} -+ & 0.002+ & 0.002+ & 0+ & 0+ \\ 0+ & -+ & 0.010+ & 0.002+ & 0+ \\ 0+ & 0.016+ & -+ & 0.003+ & 0+ \\ 0+ & 0.011+ & 0.011+ & -+ & 0+ \\ 0+ & 0.052+ & 0.048+ & 0.009+ & - \end{matrix} \right)^{-1}$$

k= 1.19

Before using equations (6.13-6.15) to find (β^m) and (M_{H_U}), we need to utilise equations (6.11-6.12) to find ($\beta^{m\prime}$), ($\bar{M}'_{H_U}$), and ($\tilde{M}'_{H_U}$):

$\bar{M}'_{H_U} = k\big(\bar{M}_{H_{12}}\bar{M}_{H_{WEnv}}\big)$ = 1.19× 0.54× 0.58= 0.37

$\tilde{M}'_{H_U} = k\big(\tilde{M}_{H_{12}}\tilde{M}_{H_{WEnv}} + \tilde{M}_{H_{12}}\bar{M}_{H_{WEnv}} + \tilde{M}_{H_{WEnv}}\bar{M}_{H_{12}}\big)$ = 1.19 ×

[(0×0)+(0.54×0)+(0×0.58)] = 0

Accordingly, when $\beta^m = \frac{\beta^{m\prime}}{(1-\bar{H}_U)}, where\ (m = 1,2,3,4,5)$, then:

$\beta^m = \frac{\beta^{m\prime}}{(1-\bar{H}_U)}\ , where\ (m = 1,2,3,4,5)$, then:

$\beta^{m\prime} = k\big(M_{12}^m M_3^m + M_{12}^m M_{H_{WEnv}} + M_3^m M_{H_{12}}\big)$

$\beta^{1\prime} = k\big(M_{12}^1 M_3^1 + M_{12}^1 M_{H_{WEnv}} + M_3^1 M_{H_{12}}\big)$ = 1.19 × [(0.01×0)+(0.01×0.58)+(0.54×0)]= 0.01

$\beta^{2\prime} = k\big(M_{12}^2 M_3^2 + M_{12}^2 M_{H_{WEnv}} + M_3^2 M_{H_{12}}\big)$ = 1.19 ×

[(0.05×0.20)+(0.05×0.58)+(0.54×0.20)] = 0.18

$\beta^{3\prime} = k\big(M_{12}^3 M_3^3 + M_{12}^3 M_{H_{WEnv}} + M_3^3 M_{H_{12}}\big)$ = 1.19 ×

[(0.08×0.19)+(0.08×0.58)+(0.54×0.19)] = 0.19

$\beta^{4\prime} = k\big(M_{12}^4 M_3^4 + M_{12}^4 M_{H_{WEnv}} + M_3^4 M_{H_{12}}\big)$ = 1.19 ×

[(0.18×0.03)+(0.18×0.58)+(0.54×0.03)]= 0.15

$\beta^{5'} = k\left(M_{12}^{5}M_{3}^{5} + M_{12}^{5}M_{H_{WEnv}} + M_{3}^{5}M_{H_{12}}\right)$ = 1.19 × [(0.14×0)+(0.14×0.58)+(0.54×0)]= 0.09

Accordingly, $\beta^{1}, \beta^{2}, \beta^{3}, \beta^{4}, and\ \beta^{5}$can be found using equation (6.14) as follows:

When, $m = 1,\ then\ \frac{\beta^{1'}}{1-\bar{H}_{U}'} = \frac{0.01}{1-0.37} = 0.01$

When, $m = 2,\ then\ \frac{\beta^{2'}}{1-\bar{H}_{U}'} = \frac{0.18}{1-0.37} = 0.29$

When, $m = 3,\ then\ \frac{\beta^{3'}}{1-\bar{H}_{U}'} = \frac{0.19}{1-0.37} = 0.31$

When, $m = 4,\ then\ \frac{\beta^{4'}}{1-\bar{H}_{U}'} = \frac{0.15}{1-0.37} = 0.24$

When, $m = 5,\ then\ \frac{\beta^{5'}}{1-\bar{H}_{U}'} = \frac{0.09}{1-0.37} = 0.15$

Furthermore, finding M_{H_U} can be done using equation (6.15) as follows:

$$M_{H_U} = \frac{\tilde{M}_{H_U}'}{1-\bar{M}_{H_U}'} = \frac{0}{1-0.37} = 0$$

As a result, the aggregation of PF criterion for the first pilot can be presented as follows (see Table 6.19):

$\widetilde{PF}_{Pilot1}$ ={(1% Neutral), (29% Slightly Fatigued), (31% Moderate), (24% Fatigued), (15% Very Bad)}

Utilising the IDS software, which can help elucidate the above example with other MPRIs for each pilot, the results are presented in Tables (6.31-6.35).

Table 6.31. Aggregation of Technical Proficiency (TP) sub-criteria

Fuzzy output		Weight		Linguistic terms				
				V. Good	Good	Average	Low	Basic
Pilot 1	$\widetilde{TP}_{QPL}$	ANP	0.089	0.36	0.64	0	0	0
		AHP	0.183					
	$\widetilde{TP}_{ST}$	ANP	0.289	0	0.20	0.80	0	0
		AHP	0.452					
	$\widetilde{TP}_{WEx}$	ANP	0.622	0	0.04	0.24	0.72	0
		AHP	0.365					
Aggregation result (ANP)				0.02	0.10	0.37	0.52	0
Aggregation result (AHP)				0.05	0.21	0.51	0.24	0
Pilot 2	$\widetilde{TP}_{QPL}$	ANP	0.089	0.04	0.32	0.64	0	0
		AHP	0.183					
	$\widetilde{TP}_{ST}$	ANP	0.289	0	0	0.20	0.80	0
		AHP	0.452					
	$\widetilde{TP}_{WEx}$	ANP	0.622	0.12	0.56	0.32	0	0
		AHP	0.365					
Aggregation result (ANP)				0.09	0.43	0.33	0.14	0
Aggregation result (AHP)				0.05	0.24	0.33	0.38	0
Pilot 3	$\widetilde{TP}_{QPL}$	ANP	0.089	0	0	0	0	1
		AHP	0.183					
	$\widetilde{TP}_{ST}$	ANP	0.289	0	0	0	0	1
		AHP	0.452					
	$\widetilde{TP}_{WEx}$	ANP	0.622	1	0	0	0	0
		AHP	0.365					
Aggregation result (ANP)				0.75	0	0	0	0.25
Aggregation result (AHP)				0.32	0	0	0	0.68

Table 6.32. Aggregation of Personal Fatigue (PF) sub-criteria

Fuzzy output		Weight		Linguistic terms				
				Neutral	S. Fatigued	Moderate	Fatigued	V. Bad
Pilot 1	$\widetilde{PF}_{WH}$	ANP	0.210	0.06	0.38	0.56	0	0
		AHP	0.113					
	$\widetilde{PF}_{WS}$	ANP	0.366	0	0	0	0.56	0.44
		AHP	0.547					
	$\widetilde{PF}_{WEnv}$	ANP	0.424	0	0.48	0.44	0.08	0
		AHP	0.340					
Aggregation result (ANP)				0.01	0.29	0.31	0.24	0.15
Aggregation result (AHP)				0	0.16	0.16	0.39	0.28
Pilot 2	$\widetilde{PF}_{WH}$	ANP	0.210	0.06	0.38	0.56	0	0
		AHP	0.113					
	$\widetilde{PF}_{WS}$	ANP	0.366	0	0	0	0.32	0.68
		AHP	0.547					
	$\widetilde{PF}_{WEnv}$	ANP	0.424	0	0	0.40	0.50	0.10
		AHP	0.340					
Aggregation result (ANP)				0.01	0.06	0.28	0.36	0.29
Aggregation result (AHP)				0	0.02	0.15	0.37	0.46
Pilot 3	$\widetilde{PF}_{WH}$	ANP	0.210	0	0	0	0.24	0.76
		AHP	0.113					
	$\widetilde{PF}_{WS}$	ANP	0.366	0	0	0.32	0.56	0.12
		AHP	0.547					
	$\widetilde{PF}_{WEnv}$	ANP	0.424	0	0	0.24	0.62	0.14
		AHP	0.340					
Aggregation result (ANP)				0	0	0.21	0.56	0.22
Aggregation result (AHP)				0	0	0.26	0.59	0.16

Table 6.33. Aggregation of Non-Technical Skills (NTS) sub-criteria

Fuzzy output		Weight		Linguistic terms				
				V. Good	Good	Moderate	Bad	V. Bad
Pilot 1	$\widetilde{NTS}_{DM}$	ANP	0.075	0.36	0.64	0	0	0
		AHP	0.074					
	$\widetilde{NTS}_{SA}$	ANP	0.155	0.14	0.56	0.27	0.03	0
		AHP	0.169					
	$\widetilde{NTS}_{CS}$	ANP	0.234	0.14	0.56	0.27	0.03	0
		AHP	0.400					
	$\widetilde{NTS}_{T\&L}$	ANP	0.536	0	0	072	0.24	0.04
		AHP	0.357					
Aggregation result (ANP)				0.05	0.19	0.57	0.16	0.02
Aggregation result (AHP)				0.09	0.36	0.44	0.10	0.01
Pilot 2	$\widetilde{NTS}_{DM}$	ANP	0.075	0.04	0.16	0.72	0.08	0
		AHP	0.074					
	$\widetilde{NTS}_{SA}$	ANP	0.155	0.12	0.48	0.36	0.04	0
		AHP	0.169					
	$\widetilde{NTS}_{CS}$	ANP	0.234	0.06	0.24	0.63	0.07	0
		AHP	0.400					
	$\widetilde{NTS}_{T\&L}$	ANP	0.536	0.12	0.48	0.36	0.04	0
		AHP	0.357					
Aggregation result (ANP)				0.09	0.42	0.45	0.04	0
Aggregation result (AHP)				0.08	0.35	0.52	0.05	0
Pilot 3	$\widetilde{NTS}_{DM}$	ANP	0.075	0.52	0.48	0	0	0
		AHP	0.074					
	$\widetilde{NTS}_{SA}$	ANP	0.155	0.36	0.64	0	0	0
		AHP	0.169					
	$\widetilde{NTS}_{CS}$	ANP	0.234	0.10	0.40	0.45	0.05	0
		AHP	0.400					
	$\widetilde{NTS}_{T\&L}$	ANP	0.536	0	0	0.36	0.52	0.12
		AHP	0.357					
Aggregation result (ANP)				0.08	0.17	0.34	0.34	0.08
Aggregation result (AHP)				0.12	0.30	0.34	0.20	0.04

Table 6.34. Aggregation of Fitness & Strength (F&S) sub-criteria

Fuzzy output		Weight		Linguistic terms				
				Fit	V. Good	Moderate	Bad	Unfit
Pilot 1	$\widetilde{F\&S}_{OA}$	ANP	0.049	0.06	0.24	0.63	0.07	0
		AHP	0.111					
	$\widetilde{F\&S}_{HI}$	ANP	0.558	0.80	0.18	0.02	0	0
		AHP	0.204					
	$\widetilde{F\&S}_{BS}$	ANP	0.393	0.80	0.18	0.02	0	0
		AHP	0.685					
Aggregation result (ANP)				0.82	0.15	0.03	0	0
Aggregation result (AHP)				0.78	0.17	0.04	0	0
Pilot 2	$\widetilde{F\&S}_{OA}$	ANP	0.049	0	0	0.63	0.31	0.06
		AHP	0.111					
	$\widetilde{F\&S}_{HI}$	ANP	0.558	0	0.72	0.26	0.02	0
		AHP	0.204					
	$\widetilde{F\&S}_{BS}$	ANP	0.393	0	0.63	0.34	0.03	0
		AHP	0.685					
Aggregation result (ANP)				0	0.70	0.28	0.03	0
Aggregation result (AHP)				0	0.62	0.34	0.04	0
Pilot 3	$\widetilde{F\&S}_{OA}$	ANP	0.049	0	0	0	0.40	0.60
		AHP	0.111					
	$\widetilde{F\&S}_{HI}$	ANP	0.558	0	0	0.90	0.10	0
		AHP	0.204					
	$\widetilde{F\&S}_{BS}$	ANP	0.393	0	0	0.72	0.24	0.04
		AHP	0.685					
Aggregation result (ANP)				0	0	0.85	0.13	0.02
Aggregation result (AHP)				0	0	0.73	0.22	0.06

Table 6.35. Aggregation of pilot reliability (PR) main criterion

Fuzzy output		Weight		Linguistic terms				
				V. High	High	Moderate	Low	V. Low
Pilot 1	PR_{TP}	ANP	0.045	0.03	0.12	0.33	0.41	0.1
		AHP	0.115	0.09	0.22	0.46	0.19	0.05
	PR_{PF}	ANP	0.186	0.07	0.26	0.28	0.19	0.20
		AHP	0.445	0.04	0.15	0.15	0.31	0.36
	PR_{NTS}	ANP	0.606	0.09	0.21	0.52	0.13	0.06
		AHP	0.365	0.16	0.33	0.39	0.08	0.03
	$PR_{F\&S}$	ANP	0.163	0.85	0.13	0.03	0	0
		AHP	0.075	0.82	0.14	0.04	0	0
Aggregation result (ANP)				0.16	0.21	0.44	0.13	0.06
Aggregation result (AHP)				0.12	0.22	0.27	0.20	0.19
Pilot 2	PR_{TP}	ANP	0.045	0.18	0.38	0.30	0.11	0.03
		AHP	0.115	0.09	0.23	0.30	0.30	0.08
	PR_{PF}	ANP	0.186	0.02	0.08	0.26	0.29	0.36
		AHP	0.445	0.01	0.03	0.13	0.30	0.53
	PR_{NTS}	ANP	0.606	0.18	0.38	0.40	0.03	0.01
		AHP	0.365	0.15	0.33	0.47	0.04	0.01
	$PR_{F\&S}$	ANP	0.163	0.14	0.58	0.25	0.02	0.01
		AHP	0.075	0.12	0.53	0.31	0.03	0.01
Aggregation result (ANP)				0.15	0.38	0.37	0.06	0.04
Aggregation result (AHP)				0.07	0.19	0.29	0.19	0.26
Pilot 3	PR_{TP}	ANP	0.045	0.75	0	0	0	0.25
		AHP	0.115	0.32	0	0	0	0.68
	PR_{PF}	ANP	0.186	0	0.02	0.19	0.45	0.34
		AHP	0.445	0	0.03	0.23	0.47	0.28
	PR_{NTS}	ANP	0.606	0.11	0.17	0.30	0.27	0.14
		AHP	0.365	0.18	0.27	0.31	0.16	0.08
	$PR_{F\&S}$	ANP	0.163	0	0.08	0.76	0.10	0.05
		AHP	0.075	0	0.07	0.65	0.17	0
Aggregation result (ANP)				0.10	0.13	0.34	0.27	0.16
Aggregation result (AHP)				0.09	0.11	0.27	0.30	0.23

6.4.7 Obtaining a pilot's reliability using utility techniques

The result obtained from the aggregation of the 4 main criteria for each pilot, as shown in Table (6.35), shows this is not a straightforward way to obtain a crisp reliability value for the assessed pilot. The utility technique used in this section aims to identify a single crisp value for the main level, which is the reliability of a pilot as the goal of this assessment model, by ranking the importance of every sub-criterion (Riahi et al., 2012). This will help when ranking each assessed pilot based on their reliability value. Using Equations (6.14-6.19) to obtain the crisp number for a pilot's reliability will allow the decision-makers to practically identify the utility value associated with the linguistic terms used to describe the degree of belief.

In Table 6.35, an aggregation process for Pilot 1's reliability is identified as follows:

When using ANP weights:

$\widetilde{PR}$ = {(Very High, 0.16), (High, 0.21), (Moderate, 0.44), (Low, 0.13), (Very Low, 0.06)}

When using AHP weights:

$\widetilde{PR}$ = {(Very High, 0.12), (High, 0.22), (Moderate, 0.27), (Low, 0.20), (Very Low, 0.19)

The fuzzy terms used to express the goal use five linguistic variables, where the highest preference term used is Very High and the lowest linguistic preference used is Very Low. The utility value for assessing the reliability of a marine pilot can be identified using equations 6.16-6.21, when using ANP weights as 0.571, and when using AHP weights as 0.476, as presented in Tables 6.36 and 6.37.

Table 6.36. The reliability value for Pilot 1 using ANP weight

$\boldsymbol{H_n}$	**Very High**	**High**	**Moderate**	**Low**	**Very Low**
$\boldsymbol{V_n}$	5	4	3	2	1
$\boldsymbol{u(H_n)}$	$\frac{5-1}{5-1}=1$	$\frac{4-1}{5-1}=0.75$	$\frac{3-1}{5-1}=0.5$	$\frac{2-1}{5-1}=0.25$	$\frac{1-1}{5-1}=0$
$\boldsymbol{\beta_n}$	0.16	0.21	0.44	0.13	0.06
$\sum_{n=1}^{5}\boldsymbol{\beta_n}$	= 0.16+ 0.21+ 0.44+ 0.13+ 0.06= 1 $\longrightarrow \beta_H = 0$				
$\boldsymbol{\beta_n u(H_n)}$	0.16	0.158	0.22	0.033	0
The reliability value for Pilot 1 = $\sum_{n=1}^{5}\beta_n u(H_n)$= 0.571					

Table 6.37. The reliability value for Pilot 1 using AHP weight

$\boldsymbol{H_n}$	**Very High**	**High**	**Moderate**	**Low**	**Very Low**
$\boldsymbol{V_n}$	5	4	3	2	1
$\boldsymbol{u(H_n)}$	$\frac{5-1}{5-1}=1$	$\frac{4-1}{5-1}=0.75$	$\frac{3-1}{5-1}=0.5$	$\frac{2-1}{5-1}=0.25$	$\frac{1-1}{5-1}=0$
$\boldsymbol{\beta_n}$	0.125	0.223	0.268	0.198	0.186
$\sum_{n=1}^{5}\boldsymbol{\beta_n}$	= 0.125+ 0.223+ 0.268+ 0.198+ 0.186= 1 $\longrightarrow \beta_H = 0$				
$\boldsymbol{\beta_n u(H_n)}$	0.125	0.1673	0.134	0.0495	0
The reliability value for Pilot 1 = $\sum_{n=1}^{5}\beta_n u(H_n)$= 0.476					

All other utility value calculations for Pilot 2 and Pilot 3 can be found in Appendix II. For further details, please refer to Appendix II.

By comparing the results obtained when using the utility value, the most eligible pilot can eventually be selected to conduct the pilotage service. This comparison must be conducted among the same pilotage rank.

6.4.8 Sensitivity analysis

To test the feasibility and the logicality of the obtained results, a sensitivity analysis based on the three axioms identified by Yang et al. (2009) is used. These three axioms are presented in Section (6.3.9) and aim to analyse how sensitive the outputs are when minor changes in input are applied. For the model to show it is robust and its inference reasoning is logical, then the sensitivity analysis must satisfy the three identified axioms.

To conduct this analysis, the degrees of belief associated with the lowest preference linguistic variables used to asses each criterion of all sub-criteria for Pilot 1 presented in Tables (6.31-6.34) are decreased by 0.1, 0.2, and 0.3. Simultaneously, the degrees of belief associated with the highest preference linguistic variables are increased in a similar way (i.e. 0.1, 0.2, and 0.3). For instance, the degree of belief of QPL for Pilot 1 as shown in Table (6.17) (Excellent, 0.36, and Professional, 0.64) shows that when an increase of 0.1 is applied to the highest linguistic preference, the lowest preference is simultaneously decreased by 0.1. In this example, the linguistic preference of (Excellent) becomes 0.46, and (Professional) becomes 0.54. However, if the lowest preference linguistic variables are less than 0.1 (i.e. 0.04), then the remaining belief degree (i.e. 0.1-0.04 = 0.06) can be taken from the next preferred linguistic variable. For instance, the $\widetilde{NTS}_{T\&L}$ for Pilot 1 on Table (6.33) shows the following evaluation:

$$\widetilde{NTS}_{T\&L} = \{(Excellent, 0), (Skillful, 0), (Moderate, 0.72), (Bad, 0.24), (Unskilful, 0.04)$$

The value of 0.04 is less than 0.1. Therefore, the next preference variable (i.e. Bad) will decrease by the remaining value of 0.06, resulting in the deduction of 0.1-0.04. As a result, the following is the evaluation of Pilot 1's $\widetilde{NTS}_{T\&L}$following the above process:

$$\widetilde{NTS}_{T\&L} = \{(Excellent, 0.1), (Skillful, 0), (Moderate, 0.72), (Bad, 0.18), (Unskilful, 0)$$

The result from the above process is applied in Tables (6.31-6.34) for Pilot 1, which is then presented in Tables (6.38-6.41). For all other pilots, the results obtained are presented in Appendix II. For further details, please refer to Appendix II.

Table 6.38. Decrement of lower preference value for technical proficiency (TP) sub-criteria

	Decrement	Linguistic terms				
		V. Good	Good	Average	Low	Basic
$\widetilde{TP}_{QPL}$	Main	0.36	0.64	0	0	0
	0.1	0.46	0.54	0	0	0
	0.2	0.56	0.44	0	0	0
	0.3	0.66	0.34	0	0	0
$\widetilde{TP}_{ST}$	Main	0	0.20	0.80	0	0
	0.1	0.1	0.20	0.70	0	0
	0.2	0.2	0.20	0.60	0	0
	0.3	0.3	0.20	0.50	0	0
$\widetilde{TP}_{WEx}$	Main	0	0.04	0.24	0.72	0
	0.1	0.1	0.04	0.24	0.62	0
	0.2	0.2	0.04	0.24	0.52	0
	0.3	0.3	0.04	0.24	0.42	0

Table 6.39. Decrement of lower preference value for personal fatigue (PF) sub-criteria

	Decrement	Linguistic terms				
		Neutral	S. Fatigues	Moderate	Fatigued	V. Bad
$\widetilde{PF}_{WH}$	Main	0.06	0.38	0.56	0	0
	0.1	0.16	0.38	0.46	0	0
	0.2	0.26	0.38	0.36	0	0
	0.3	0.36	0.38	0.26	0	0
$\widetilde{PF}_{WS}$	Main	0	0	0	0.56	0.44
	0.1	0.1	0	0	0.56	0.34
	0.2	0.2	0	0	0.56	0.24
	0.3	0.3	0	0	0.56	0.14
$\widetilde{PF}_{WEnv}$	Main	0	0.48	0.44	0.08	0
	0.1	0.1	0.48	0.42	0	0
	0.2	0.2	0.48	0.32	0	0
	0.3	0.3	0.48	0.22	0	0

Table 6.40. Decrement of lower preference value for non-technical skills (NTS) sub-criteria

Decrement		Linguistic terms				
		V. Good	Good	Moderate	Bad	V. Bad
$\widetilde{NTS}_{DM}$	Main	0.36	0.64	0	0	0
	0.1	0.46	0.54	0	0	0
	0.2	0.56	0.44	0	0	0
	0.3	0.66	0.34	0	0	0
$\widetilde{NTS}_{SA}$	Main	0.14	0.56	0.27	0.03	0
	0.1	0.24	0.56	0.20	0	0
	0.2	0.34	0.56	0.10	0	0
	0.3	0.44	0.56	0	0	0
$\widetilde{NTS}_{CS}$	Main	0.14	0.56	0.27	0.03	0
	0.1	0.24	0.56	0.20	0	0
	0.2	0.34	0.56	0.10	0	0
	0.3	0.44	0.56	0	0	0
$\widetilde{NTS}_{T\&L}$	Main	0	0	0.72	0.24	0.04
	0.1	0.1	0	0.72	0.18	0
	0.2	0.2	0	0.72	0.08	0
	0.3	0.3	0	0.70	0	0

Table 6.41. Decrement of lower preference value for fitness & strength (F&S) sub-criteria

Decrement		Linguistic terms				
		Fit	Good	Moderate	Bad	Unfit
$\widetilde{F\&S}_{OA}$	Main	0.06	0.24	0.63	0.07	0
	0.1	0.16	0.24	0.60	0	0
	0.2	0.26	0.24	0.50	0	0
	0.3	0.36	0.24	0.40	0	0
$\widetilde{F\&S}_{HI}$	Main	0.80	0.18	0.02	0	0
	0.1	0.90	0.10	0	0	0
	0.2	1	0	0	0	0
	0.3	1	0	0	0	0
$\widetilde{F\&S}_{BS}$	Main	0.80	0.18	0.02	0	0
	0.1	0.90	0.10	0	0	0
	0.2	1	0	0	0	0
	0.3	1	0	0	0	0

According to the above increment and decrement process, the utility value for the goals in accordance with these changes when using ANP and AHP weights are presented on Tables (6.42-6.43), and a graph is drawn on Figures (6.8-6.9).

Table 6.42. Alteration of the median of Pilot 1's reliability using ANP weights

Sub-criterion	Alteration of the median reliability value of a pilot due to the following decrease in the degree of belief associated to the lowest preferences linguistic term of the median fuzzy set of each sub-criterion			
	Main	**- 0.1**	**- 0.2**	**- 0.3**
QPL	0.5690	0.5690	0.5690	0.5691
ST	0.5690	0.5693	0.5695	0.5698
WEx	0.5690	0.5707	0.5723	0.5739
WH	0.5690	0.5701	0.5712	0.5723
WS	0.5690	0.5734	0.5777	0.5821
WEnv	0.5690	0.5738	0.5771	0.5803
DM	0.5690	0.5696	0.5702	0.5709
SA	0.5690	0.5742	0.5786	0.5831
CS	0.5690	0.5742	0.5786	0.5831
T&L	0.5690	0.6141	0.6548	0.6918
OA	0.5690	0.5692	0.5693	0.5694
HI	0.5690	0.5704	0.5715	0.5715
BS	0.5690	0.5704	0.5715	0.5715

Table 6.43. Alteration of the median of Pilot 1's reliability using AHP weights

Sub-criterion	Alteration of the median reliability value of a pilot's duo to the following decrease in the degree of belief associated to the lowest preferences linguistic term of the median fuzzy set of each sub-criterion			
	Main	**- 0.1**	**- 0.2**	**- 0.3**
QPL	0.4762	0.4763	0.4765	0.4766
ST	0.4762	0.4784	0.4806	0.4828
WEx	0.4762	0.4788	0.4813	0.4839
WH	0.4762	0.4778	0.4793	0.4809
WS	0.4762	0.5090	0.5415	0.5736
WEnv	0.4762	0.4878	0.4948	0.5020
DM	0.4762	0.4764	0.4767	0.4769
SA	0.4762	0.4793	0.4820	0.4847
CS	0.4762	0.4793	0.4820	0.4847
T&L	0.4762	0.4884	0.4995	0.5097
OA	0.4762	0.4764	0.4765	0.4766
HI	0.4762	0.4763	0.4765	0.4765
BS	0.4762	0.4763	0.4765	0.4765

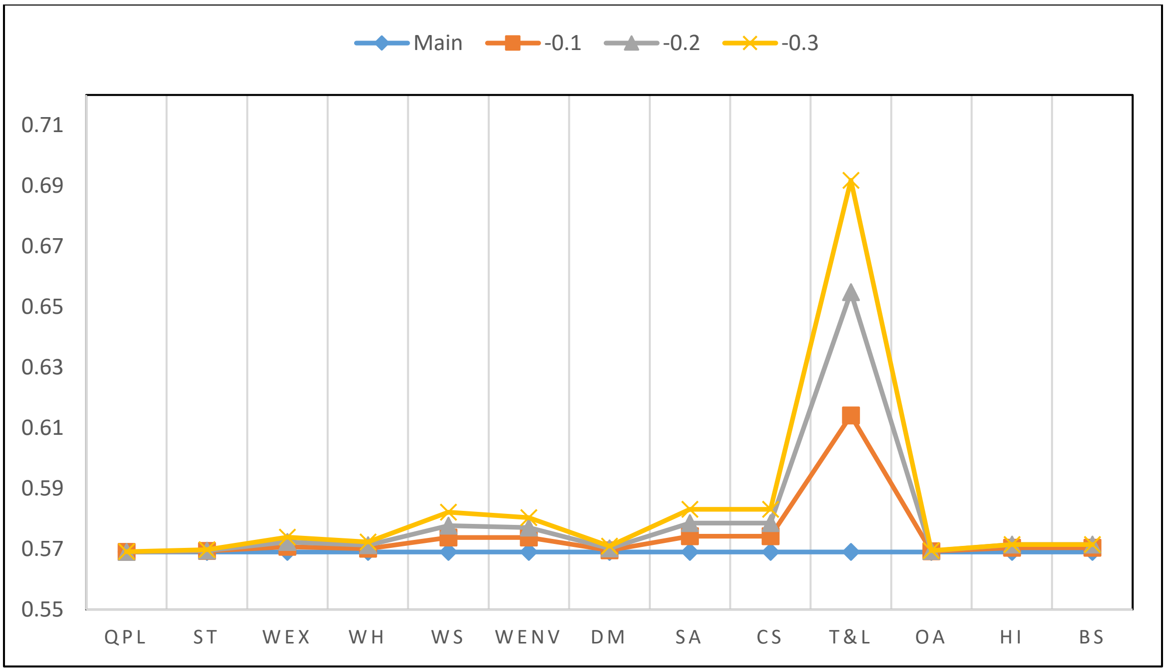

Figure 6.8. Model sensitivity output for Pilot 1 using ANP weights

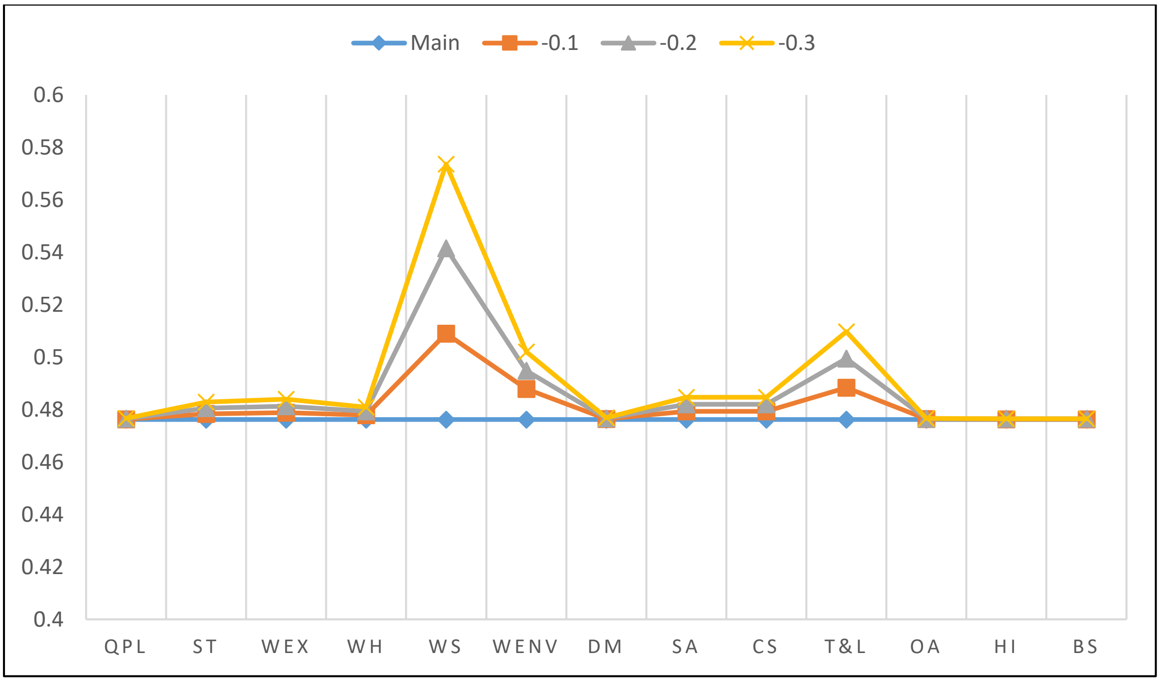

Figure 6.9. Model sensitivity output for Pilot 1 using AHP weights

Following the proof of the effectiveness of the reliability model for assessing the reliability of marine pilots, Table 6.44 shows the reliability value for the given information for all involved pilots in this assessment using the ANP weights as this research considers these factors to be interdependent.

Table 6.44. The reliability value based on the main information

MPRI		Reliability value			
		Pilot 1	**Pilot 2**	**Pilot 3**	**Ranking**
Goal	**Overall Reliability**	**0.5710**	**0.6316**	**0.4341**	**2 > 1 > 3**
Main criterion	**TP**	0.3875	0.6425	0.7519	**3 > 2 > 1**
	PF	0.4525	0.2825	0.2469	**1 > 2 > 3**
	NTS	0.5400	0.6725	0.4574	**2 > 1 > 3**
	F&S	0.9575	0.7050	0.4560	**1 > 2 > 3**
Sub-criterion	**TP-QPL**	0.8400	0.6000	0.0000	**1 > 2 > 3**
	TP-ST	0.5500	0.3000	0.0000	**1 > 2 > 3**
	TP-WEx	0.3300	0.7000	1.0000	**3 > 2 > 1**
	PF-WH	0.6250	0.6250	0.0600	**1 = 2 > 3**
	PF-WS	0.1400	0.0800	0.3000	**3 > 1 > 2**
	PF-WEnv	0.6000	0.3250	0.2750	**1 > 2 > 3**
	NTS-DM	0.8400	0.5400	0.8800	**3 > 1 > 2**
	NTS-SA	0.7025	0.6700	0.8400	**3 > 1 > 2**
	NTS-CS	0.7025	0.5725	0.6375	**1 > 3 > 2**
	NTS-T&L	0.4200	0.6700	0.3100	**2 > 1 > 3**
	F&S-OA	0.5725	0.3925	0.1000	**1 > 2 > 3**
	F&S-HI	0.9450	0.6750	0.4750	**1 > 2 > 3**
	F&S-BS	0.9450	0.6500	0.4200	**1 > 2 > 3**

6.5 Conclusion

This study has presented a novel dynamic marine pilot reliability measurement tool that deals with MPRI's interdependence rather than independence. The proposed model shows an effective reliability measurement tool capable of predicting the reliability of a marine pilot. The distinct features between the AHP and the ANP are discussed in detail in Chapters 4 and 5. Due to variations between the methods, the reliability values are different. Using the information given in the test case, the reliability of three pilots was assessed based on the proposed MPRIs and the research methods. The reliability values for each pilot are presented in Table 6.44, showing the reliability value for each criterion and sub-criterion. This table provides decision-makers with a diagnostic tool that highlights the most significant factors for mitigating degradation of the reliability level and further improving reliability. The decision-makers can identify the strengths and weaknesses of the selected pilot in terms of each individual MPRI. In our example of Pilot 1, based on the model sensitivity output shown in Figure 6.8, the most significant criterion with the highest impact on pilot reliability during a pilotage operation was found to be teamwork and leadership skills, while communication skills, situation awareness, work stress, and working environment have equivalent effects on pilot reliability. On the other hand, when factors are considered independently, the model sensitivity output presented in Figure 6.9 shows work stress to have the highest impact on pilot reliability, followed by teamwork and leadership skills, situation awareness, and communication skills. As aforementioned, this research proposed an MPRI to assess the reliability of a marine pilot in a holistic form. This approach recognises that MPRIs are interdependent and influence each other. The results reveal a difference in the evaluation due to the dissimilarity in methods used. However, the pilot's reliability is not fixed and is subject to change depending on various conditions.

The reliability value for Pilot 1 was evaluated as follows (Figure 6.10): 16 per cent Very High, 21 per cent High, 44 per cent Moderate, 13 per cent Low, and 6 per cent Very Low, with a reliability value of 0.5710. Pilot 2 was evaluated as (Figure 6.11): 15 per cent Very High, 38 per cent High, 37 per cent Moderate, 6 per cent Low, and 4 per cent Very Low, with a reliability value of 0.6316. Pilot 3 was evaluated as (Figure 6.12): 10 per cent Very High, 13 per cent High, 34 per cent Moderate, 27 per cent Low, and 16 per cent Very Low, with a reliability value of 0.4341.

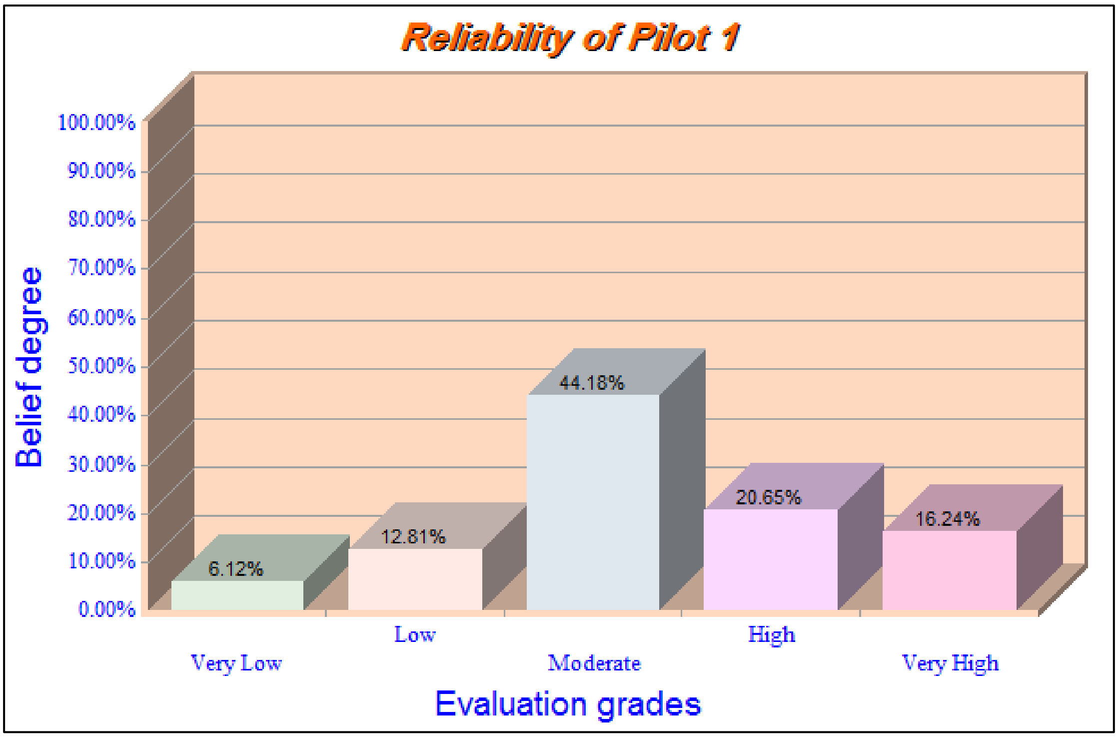

Figure 6.10. Reliability evaluation for Pilot 1

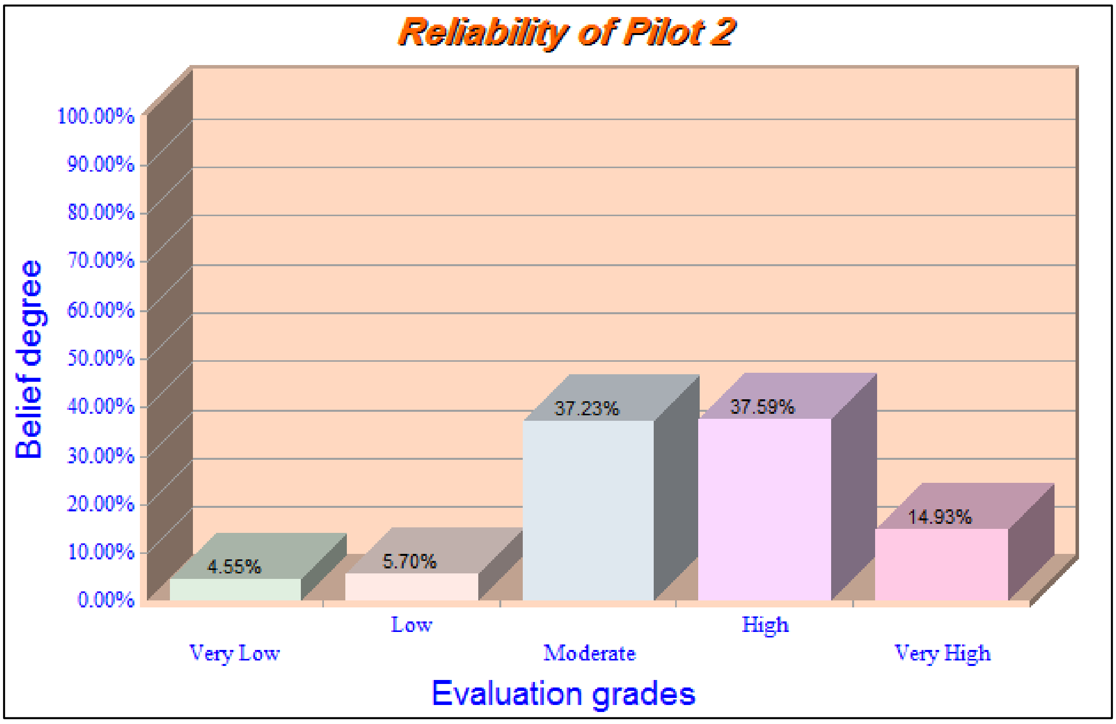

Figure 6.11. Reliability evaluation for Pilot 2

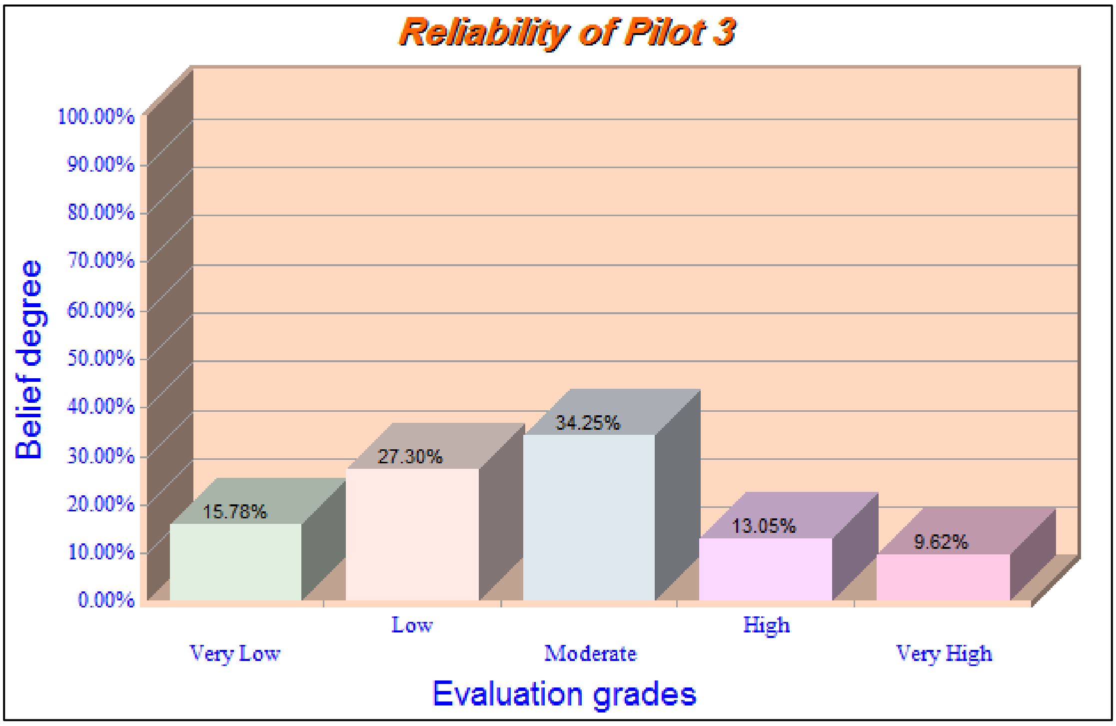

Figure 6.12. Reliability evaluation for Pilot 3

According to the findings obtained from applying a decrement on the lowest preference (Table 6.42) and the sensitivity analysis shown in Figure (6.8), changing the conditions based on the mentioned highest-ranked factors enhances the reliability value of each pilot. For example, if work stresses, teamwork/leadership skills, and working environment are the main top three criteria that influence pilot reliability, changing the condition of these criteria by 100% towards the best grades for these factors results in the following new assessment:

Pilot 1: 81% Very High, 12% High, 6% Moderate, 1% Low and 0% Very Low, with an overall reliability value of 93.15%;

Pilot 2: 69% Very High, 14% High, 16% Moderate, 1% Low and 0% Very Low, with an overall reliability value of 87.31%; and

Pilot 3: 75% Very High, 10% High, 11% Moderate, 2% Low and 2% Very Low, with an overall reliability value of 88.70%.

However, the criteria also have an influence on one another. For example, if the pilot is working in a highly stressful working environment, his health level will degrade accordingly. In addition, if the working environment is bad, and the pilot is under stress due to prolonged working hours or working at night, his situational awareness will decrease due to limitations on thinking capacity resulting from fatigue, on top of other observable deteriorations in his health in some cases. Moreover, if the pilot has a high level of experience (i.e. is an expert pilot) with high qualifications and professional training, he is most probably older. However, although it was evidenced that, when a pilot gets older, his level of experience will eventually increase, his physical strength and health, in most cases, will naturally deteriorate accordingly, and his ability to think clearly will be affected. A port authority needs expert operators to conduct pilotage operations. Therefore, the port's strategic planner must highlight requirements to improve pilotage operation reliability by considering the importance of the human reliability analysis in order to evaluate the factors that influence the level of operation efficiency and quality.

To summarise, the objectives of this chapter have been achieved by assessing the pilotage operation's reliability by highlighting the key elements that significantly affect a pilot's reliability. The model has been validated, which offers decision-makers a suitable tool for predicting these factors in ample time. Therefore, the human reliability analysis has been found significant for operational safety, where the human element, due to dramatic developments in the shipping industry, has been found to be the main root of every accident. Further empirical studies are required to benchmark the reliability of a marine pilot by conducting more investigations in different ports and at different expert levels and ranks to determine the most effective practices and solutions for further improvement on weaker identified factors.

Chapter seven: Discussion and conclusion

7.1 Chapter summary

This chapter discusses and summarises the achievements and contributions of the study, as well as study limitations and areas for further research. The chapter begins by discussing the achievements and methods used to achieve the stated research objectives. The chapter also highlights the contributions of the study. Finally, the chapter addresses the limitations of the study and recommends areas to be investigated by future research in order to enhance the developed reliability model.

7.2 Research achievements

This research is comprised of four main work packages. The main achievements, along with the research methods used, were highlighted in order to achieve the research stated objectives and that as follows:

7.2.1 Obtaining objectives one and two

The research objectives one and two aim to identify the key factors that shape marine pilot reliability based on the current operational practices to build a rational MPRI that enables decision makers to assess the reliability of a marine port pilot to ensure safer operational standards. These two objectives have been achieved in chapter 2 and 3. The marine industry is complex and highly dynamic in nature, and it is subject to a high level of uncertainty. Due to a lack of information and consensus on the main factors shaping the reliability of an operator, a qualitative based analysis was conducted via employing three different tools that prove its power in elucidating required information. These tools help to understand current operational practices and involve the expert in questions exhibiting their concerns in regards to their safety. Moreover, sequential exploratory mixed-method paradigms were selected subject to the nature of the required information and research objectives. Three qualitative tools were used to collect the required data, namely operational observation, semi-structured focus-group interviews, and port accident data analysis.

The reason to conduct a field observation was to investigate field experience, represent social activities, and understand social processes within the acquired field. Since the literature does not provide insight into the nature of the pilotage operation and the degree of interactions between various parties working there, the use of field observation has been decided upon to identify the main key operational players involved in the marine pilotage service. Moreover, this step helps identify the degree of interactions among these players to draw a full picture on how the operation is conducted and highlight the significant risk factors surrounding the operation. Five key operational players are involved in pilotage operations with various operational objectives and duties, namely shipmasters, pilots, tug masters, VTS operators, and harbour masters. However, this research mainly focuses on assessing the reliability of a marine port pilot, and the rest of the operators are left for further future investigations.

The second tool for collecting the required data was applied through conducting semi-structured focus-group interviews. The semi-structured focus-group interviews were found valuable to this research in terms of gathering the required information to build the assessment model based on expert opinions. It is ideal to explore the complexity surrounding the reliability of operators who are subject to daily influences that affect their performance, behaviour, and attitude at work. This can be achieved by encouraging participants to engage positively with the process of the research. Unlike any other research tools, this tool has some drawbacks which have been highlighted throughout the research process. Moreover, the researcher considered this issue via employing an assessment tool in the following chapter to confirm the outputs from the interviews. 35 pilots participated actively in the interview, and they were grouped into three groups. They freely offered their opinions, and the interviews have been analysed. This analysis resulted in developing the first hierarchal pilot reliability model. This model was tested in the following work package to ensure the consistency of the identified criteria.

The last tool used for collecting the data was accident data analysis. The main aim of this section is to promote the researcher's understanding of the current organisational standards applied in daily operational practices. Accident investigation adds valuable insight into the current phenomena surrounding the operational practices that influence operator reliability. This approach makes vital contributions to this study by looking back on existing operational accidents to determine the facts surrounding the cause of an accident and identifying the contributory factors leading up to the event. In addition, accident investigation plays a fundamental role in meeting the objectives of this study and provides a clear overview of operational safety issues that imply urgent operational, managerial, and structural changes in the form of regulatory levels. This is done in order to improve future system safety and accident prevention through recommendations and corrective actions. Four incidents were overviewed, aiming to highlight the significance of these accident/incidents to the overall safety, describe operational practices, and discover the main contributory factors. Surprisingly, one of these incidents occurred during the field data collection, and the researcher was asked to get involved in the investigation. The result from this chapter achieves its aim and answers one of the main research questions of, 'What are the main factors shaping the reliability of a marine pilot?'. Four main factors are detailed that are believed essential by the experts in shaping their reliability. Thirteen sub-factors which work to shape these four main factors are also described. These factors were arranged in a hierarchy structure forming a marine pilot reliability index (MPRI). Although these factors are essential in shaping the reliability of a marine pilot, there are other factors such as managerial and policymaker practices which remain essential in overall operational reliability. However, they are out of the scope of this research.

7.2.2 Obtaining objective three

The research objective three aims to examine the degree of consensus among experts on the selected factors and highlight the degree of importance of each criterion towards shaping the reliability of marine pilots. This objective has been achieved in chapter 4. The researcher has employed two research tools. The first was based on a confirmatory approach called the Delphi technique. The second tool, called the analytical hierarchy process (AHP), aims to find the degree of importance of a criterion with its associated upper criteria. The aforementioned approach helps cope with the drawbacks resulting from the interviews. During the interviews, each group was formed for interviews ranging between 10 and 12 pilots. The pilots formed different ranks, some being senior and some being junior. The seniors where highly experienced, and some of them were the supervisors of the group. This created, to some extent, an issue to encourage the juniors to participate proactively and be open to show their concerns freely due to feeling shy. This is one of the drawbacks of focus-group interviews. The Delphi approach was used to cope with this issue, as it gave the participants a higher level of anonymity throughout the investigation. This was done through a series of questionnaires sent out to experts electronically. In this research, two rounds were conducted. In the first round, 35 participants answered the designed and open-ended questionnaire to offer their opinions more freely concerning the identified factors. The aim of an open-ended questionnaire is to give the participant the opportunity to explain their selection or provide their beliefs around the identified factor. Moreover, agreement was achieved among participants through the first round with an acceptable inter-quartile range as per the method process. The second round aimed to return the questionnaire to the same participants, showing their individual answers along with the group answers. This step sought to give the participant a chance to reconsider their answer. However, they were asked to give a reason for not changing their answer. The result shows a slight improvement in the results in the second round compared with the first round.

The second method used in this chapter was the AHP. This method aimed to rank the identifiable criterion based on the experts' opinions. The same participant involved in the interview and Delphi participated here, and the result shows that the marine pilot ranked as the first important key player involved in pilotage operations, followed by the tug master, shipmaster, harbour master, and the VTS operator. This can justify the significant role that pilots play in ensuring the safety of pilotage operations. Moreover, the investigation revealed that it is common that the shipmaster is over reliant on the pilot to conduct operations. This seems to be done to decrease the shipmaster's operational stresses. Shipmasters are subject to higher operational demands (i.e. quick turnaround, loading and unloading, managerial process) which resulted in handing over the command to the marine pilot. The marine pilotage key players are subjected to higher levels of operational stresses, which are found to significantly influence their reliability. Other factors concerning organisational practices were found to be essential, and these were suggested for further investigation. Nonetheless, this issue complicates the operational environment to some extent, as it was found significant in maintaining operator reliability. This is one issue noticed throughout the observation process in chapter three, and it was also left open for further future investigation. On the other hand, the participants ranked the identified four main criteria that were found central to shaping operator reliability as follows: personal fatigue (0.4451), non-technical skills (0.3643), technical proficiency (0.1154), and fitness and strength (0.0751) as first, second, third, and fourth respectively. The following outlines the beliefs of experts involved in this research about the degree of importance of these main criteria in shaping their reliability. Factors constituting operators' technical proficiency are: qualification and pilotage licencing (QPL), special training (ST), and work experience (WEx). These factors were ranked based on their degree of importance using the AHP method as special training (0.4518), working experience (0.3651), and qualification, and pilotage licencing (0.1832) as first, second, and third respectively. Similarly, factors constituting personal fatigue were ranked from highest to lowest as follows: work stresses (0.5472), working environment (0.3394), and working hours (0.1134). Moreover, factors constituting non-technical skills were ranked as follows: communication skills (0.3996), teamwork and leadership skills (0.3573), situation awareness (0.1690), and decision making skills (0.0740). Lastly, factors constituting operator's fitness and strength are ranked as follows: body strength (0.6847), health issues (0.2041) and operator age (0.1112), respectively. It is worth mentioning that the AHP method was used to rank the MPRIs in accordance with their inner-dependencies among each other and with their associated upper main criterion. However, the degree of interdependencies among MPRIs are essential to the discussions with the expert. Therefore, chapter 5 has proposed a method that is capable of identifying the degree of interdependencies among MPRIs.

7.2.3 Obtaining objective four

The research objective four aims to identify the degree of interactions among the identified factors to enable the decision makers to predict the possibility of reliability fluctuations. This objective has been achieved in chapter 5, as the degree of interdependencies among MPRIs have been detailed. It was found that developing a network instead of a hierarchy helps decision makers to understand and identify the cause and effect relationship between criteria. Meanwhile, the hierarchal model allows decision makers to examine the responses between factors. The AHP method used in the previous chapter can identify the interdependencies between factors only within the cluster, while the non-linear strategy can identify the degree of interdependencies among clusters and within a cluster. The non-linear strategy represents the ANP method. In this chapter, the researcher used a hybrid form method called FDEMATEL and ANP. This hybrid approach was used because it was difficult to quantify precise values when evaluating a complex system. Moreover, this approach allowed the researcher to easily divide a complex system into subsystems and then carry out an effective measurement. The objective behind the invention of FDEMATEL was to investigate and solve social complexity and intertwined problems in an uncertain working environment. This method has a structural approach that distinguishes between cause and effect, and developed an influential network relation map. Following the development of an initial direct relation matrix, normalising direct relation matrix, total relation matrix, and the identification of the threshold value, the direct and indirect relation between MPRIs were identified. Three of the main factors constituting the MPRIs have been identified as cause factors which influence the reliability of a marine pilot, while the fourth plays as an effect factor. Moreover, nine of the MPRIs have been identified as cause factors which influence the reliability of a marine pilot, while four of the MPRIs play as effect factors. Following this step, the researcher used an analytical network process (ANP) to reweight the identified factors based on the result of the cause and effect created by the FDEMATEL approach. The result showed the global weight of the MPRIs, which means that each sub-factor constituting the lower level of the MPRIs has a degree of influence on each factor in the developed indicator. Accordingly, the five highest important factors are teamwork and leadership skills (0.325), communication skills (0.142), situation awareness (0.094), health issue (0.091), and working environment (0.079). This can be interpreted as operator non-technical skills significantly shaping operator reliability. This is because the operation requires higher levels of interpersonal skills to make proper decisions. This is in line with the recommendation of the IMO to implement a bridge resource management course for all pilots which can enhance theses skills. Moreover, the significance of the health issue was observed throughout the interviews, since this issue grows due to higher operational demands, stresses, and fatigue. The pilot must maintain an acceptable level of physical capability to conduct the operation. Some port authorities conduct a periodical physical assessment for pilots to evaluate their capability to conduct pilotage services, as pilotage services require a higher level of fitness and strength. In addition, working environment has a significant role in ensuring the reliability of a marine pilot at a higher level. This can be maintained through a series of managerial actions such as introducing learning opportunities, promotion, encouragement, and maintaining pilot scheduling.

7.2.4 Obtaining objectives five and six

The research objectives five and six aim to develop an effective systematic quantitative human reliability measurement tool and test it via conducting a real case study to assess the reliability of a marine port pilot and validate the proposed MPRI. Accordingly, an empirical reliability assessment was carried out practically. Based on the information given in the test case, three pilots were assessed based on the developed MPRIs and the use of the proposed method of fuzzy evidential reasoning (FER) based on a fuzzy rule approach. The proposed model is proven to be an effective reliability measurement tool capable of predicting the reliability of a marine pilot.

The reliability values for each pilot were identified using a utility technique for each criterion and sub-criterion, which offers decision makers a diagnostic tool to highlight the most significant factors to mitigate the consequences of factors that degrade reliability levels. Decision makers can identify the strengths and weaknesses of the selected pilot in terms of each individual MPRI. The given example of Pilot 1, based on the model sensitivity output when using ANP weights, the most significant criterion that has the highest impact on pilot reliability during a pilotage operation was found to be teamwork and leadership skills. Meanwhile communication skills, situation awareness, work stresses and working environment are showing an equivalent effect on pilot reliability.

However, the pilot's reliability is not fixed, and it is subject to change depending on various conditions.

Table 6.44 presents findings on the overall reliability value as well as the reliability value for each main-criterion and sub-criterion for all assessed marine pilots which can be used for ranking the pilots, based on their reliability. A higher reliability value indicates that a pilot has a larger capacity to conduct the operation. The decision maker also has the ability to identify strengths and weaknesses of each pilot, based on his/her reliability value identified for each sub-criterion to improve the reliability of a pilot rationally. As shown in Table 6.44, Pilot 2 was ranked first, based on overall reliability value, followed by Pilots 1 and 3, respectively. When the decision makers look at the sub-criterion, Pilot 3 was ranked first, based on his main sub-criterion TP, followed by Pilots 2 and 1, respectively. In addition, when looking at lower level criteria, variance on reliability values among the three pilots was evident. However, the decision makers were urged to give extra emphasis to criterion with higher degrees of importance, as obtained when using techniques such as AHP and ANP. In this study, for instance, the top five important criteria obtained by ANP were T&L, CS, SA, HI, and WS, respectively. In this case, for example, the decision makers may select the higher reliability value among experts, based on the top important criterion, which plays a significant role in overall marine pilot reliability. Moreover, the decision maker may provide extra support to the pilot to improve operational outcomes, based on the value obtained.

The top identified important criterion was T&L. The lower reliability value in this criterion among the pilots was given to Pilot 3, followed by Pilot 2, with the top being Pilot 1. In this case, the decision maker may be involved in solving conflicts between team members. When Pilot 3 is involved in operations, it is essential to provide training, add another pilot to support this pilot, or even replace the pilot with a pilot with reliability value in this criterion. However, the significance of other criteria must not be neglected. Instead, the overall weighing and balancing of criteria must be conducted by decision makers to select the most appropriate pilot to conduct the operation.

According to the findings obtained from applying a decrement on the lowest preference and sensitivity analysis, changing the conditions based on the mentioned highest-ranked factors enhances the reliability value of each pilot. For example, if work stresses, teamwork/leadership skills, and working environment are the top three criteria that influence pilot reliability, changing the condition of these criteria by 100 per cent towards the best grades for these factors results in the following new assessment:

Pilot 1: 81 per cent Very High, 12 per cent High, 6 per cent Moderate, 1 per cent Low and 0 per cent Very Low, with an overall reliability value of 93.15%;

Pilot 2: 69 per cent Very High, 14 per cent High, 16 per cent Moderate, 1 per cent Low and 0 per cent Very Low, with an overall reliability value of 87.31%; and

Pilot 3: 75 per cent Very High, 10 per cent High, 11 per cent Moderate, 2 per cent Low and 2 per cent Very Low, with an overall reliability value of 88.70%.

However, the criteria also have an influence on one another. For example, if the pilot is working in a highly stressful working environment, his health level will degrade accordingly. In addition, if the working environment is bad, and the pilot is under stress due to prolonged working hours or working at night, his situational awareness will decrease due to limitations on thinking capacity resulting from fatigue, on top of other observable deteriorations in his health in some cases. Moreover, if the pilot has a high level of experience (i.e. is an expert pilot) with high qualifications and professional training, he is most probably older. However, although it was evidenced that, when a pilot gets older, his level of experience will eventually increase, his physical strength and health, in most cases, will naturally deteriorate accordingly and his ability to think clearly will be affected. A port authority needs expert operators to conduct pilotage operations. Therefore, the port's strategic planner must highlight requirements to improve pilotage operations reliability by considering the importance of the human reliability analysis in order to evaluate the factors that influence the level of operational efficiency and quality.

In summary, the objectives of this chapter have been achieved through assessing the pilotage operation's reliability to highlight the key elements that significantly affect a pilot's reliability. The model has been validated, which offers decision makers a suitable tool for predicting these factors in ample time. Therefore, the human reliability analysis has been found significant for operational safety. This is because the human element, due to dramatic developments in the shipping industry, has been found to be the main cause of every accident. Further empirical studies are required to benchmark the reliability of a marine pilot. More investigations could be conducted in different ports at different expert levels and ranks to determine the most effective practices and solutions for further improvements on identified weaker factors.

7.3 Research contribution

This research's main contribution was forming a novel marine pilot reliability index (MPRI) aimed at assessing the reliability value for estimating, controlling, and monitoring operator performance as a complete system. The research framework is comprised of relevant tools and techniques that prove their capabilities to perform required assessment for measuring, evaluating, and controlling operational influences that affect the desired functions of marine pilots. The study integrated assessments of personal and interpersonal aspects believed essential in shaping the reliability of a marine pilot in a complex working environment. The developed assessment models are believed to be powerful to assess the reliability and have been tailored to assess marine pilots. The model can assist port decision makers to prevent risks associated with factors affecting pilot reliability. Furthermore, the models work to find links between the featured factors to trace the initiatives of reliability degradation in the early stages. The developed model is believed to have the potential to enhance the awareness of decision makers in identifying potential risks associated with a highly uncertain and complex working environment.

The originality and novelty of this work is due to the following:

1- Highlighting the research and operational gap within port industries that urgently needs to be covered;
2- Developing a holistic marine pilot’s reliability index through linking factors affecting human performance and finding the interrelationship between them as one set;
3- Estimating the degree of influence among the identified MPRIs through providing an effective tool providing the local and global weights for each MPRI to measure the significance of that MPRI on operator performance; and
4- Providing a novel quantitative human reliability assessment tool for decision makers to value the reliability of pilots within pilotage operations.

The key achievement of these accomplishments was the synthesis among research methods via adopting qualitative assessment methods into several multi-criteria decision-making approaches (Delphi, AHP, FDEMATEL, and ANP). The outputs are integrated into a decision-making technique (i.e. FER) to enable decision makers to improve the safety of pilotage. In addition, the sensitivity analysis was adopted as a widely recognised validation method to measure the sensitivity of the developed model by performing a sequence of tests. Although it is not decisive, the framework provides a comprehensive reliability model to analyse human reliability comprising many approaches and techniques to facilitate the acquisition of quantitative and qualitative data in maritime engineering operations.

7.4 Limitations and recommendations for further research

A number of issues were raised throughout the research process. Some of these issues are analysed, described, and merged into the study. However, some issues could not be incorporated due to scope and time constraints. Also, the present research has conspicuously been exploratory, experimental, and correlational. In this regard, incorporated issues that were not covered in much detail are part of the suggestions that would be recommended for further investigations as follows.

1- This research has focused on assessing the reliability of a marine pilot. However, there are other key players on marine pilotage services, such as the tug master, shipmaster, harbour master, and VTS operator. Each of these individuals has reliability shaping factors (Riahi et al., 2012) that must be considered in the first stage. To cope with this issue and to work in parallel with this investigation conducting a qualitative investigation is recommended to understand the nature of the factors affecting other key players. The variance on the selected criteria were found to vary, as the factors affecting VTS operator, for instance, are not similar to those affecting the tug master in terms of work place design and ergonomics.

2- This research could be extended to cover wider experimental examination to identify more reliability shaping indicators. Moreover, the application of the Delphi method proved that increasing the number of participants will provide more reliable outputs that do not change over time. Therefore, it is highly recommended to cover a wider number of participants with different cultural backgrounds in different port jurisdictions.

3- The influence of other factors highlighted briefly throughout this investigation, such as cultural diversity, different port policies, management influence, safety culture, and privatisation, are recommended to be incorporated into the assessment as external factors affecting the reliability of the operation.

4- The proposed methods are required to be assorted to the above recommendations to complete the whole picture of this work. Although these tools prove their applicability to handle the issue, more powerful tools may exist.

5- The assessment grades used and the involvement of the subjective judgements have drawbacks. However, these drawbacks can be addressed by developing more rational and effective assessments for each of the identified criteria by taking previous assessments used across different industries for monitoring factors, such as fatigue evaluation and psychological degradation.

6- The assessments have been conducted covering three pilots at the same port with wide variances in their abilities. However, it is recommended to address all pilots' reliability within the port as well as across different ports, either within the same country, same pilotage jurisdiction, or in public or private ports to address further improvement needs to the industry.

The human reliability assessment framework proposed for this research has the potential to facilitate a reliability assessment tool for port operations in a wider context. This framework must be appropriately tailored to study other topics indicated for further recommendation. The framework will also offer practical guidance outside of the maritime industry on steps to be taken in implementing an action plan for best practices and enhancing management and operator reliability within the system as a whole.

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Appendix I: Questionnaires

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PARTICIPANT INFORMATION SHEET

Title of the Research: A novel Harmonised Decision Making Support System (HDMSS) to enhance the reliability and efficiency of port pilotage operations

Researcher name, school and faculty

My name is Atiyah A. Atiyah and I am a PhD candidate at Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, in the faculty of Engineering and Technology at Liverpool John Moores University (LJMU), UK. Before deciding to participate in this research, it is important for you to understand why the research is being conducted and what it involves. Please kindly take your time reading the following information. Do not hesitate to ask me or my supervisor or to contact the ethical committee through the contact details provided at the bottom of this sheet if you would like more information or have any complaints. Take your time to decide whether you wish to participate or not.

1. What is the purpose of the study?

The main objective of this study is to develop a marine pilot reliability index (MPRI), which will assist decision-makers in predicting changes in a pilot's performance so as to maintain operational efficiency. The index will also help in port management for improving operational standards and procedures and enable port authorities to enhance the reliability of the marine pilotage operation.

To develop this MPRI, an assessment framework has been built in a hierarchy structure consisting of three levels so as to ensure the validity and reliability of the proposed framework. The Delphi Expert Panel, of which you will be a member, consists of a number of expert pilots who have been selected anonymously to participate in this study. The panel will significantly contribute to the success of this study in two ways. Firstly, the expert pilots will be asked to give comments and opinions on the rationality and validity of the proposed assessment framework via a short structured open-ended questionnaire. This process will take three rounds of questionnaires until a consensus is achieved. Secondly, in order to assign the weight to each criterion finalised by the Delphi method, each expert member will score individually the importance of all the attributes in the framework through pairwise comparisons technique. This step will take place after a consensus is achieved. This stage aims to weigh the proposed attributes. It is important to note that each questionnaire will be available for two weeks to the experts. The data collected from each round will be analysed until the questionnaire is returned with feedback for the second round, and so forth. The analysis process may take a month to complete.

2. Do I have to take part in this study?

No, it is up to you to decide whether to take part or not. In both cases, and before you decide, you will be given this information sheet and the questionnaire link to allow you to think about whether you wish to participate. Through the link, and before you begin answering questions, you have to read the statement of consent. If you wish at this point to participate, just click as appropriate. At this stage, if you click 'I am happy to participate', I would like to thank you, as this will take you to answering the questions. However, if you click 'I do not want to participate', this will end the process without you seeing the questions. Although I will be disappointed to lose your valuable opinion, I appreciate your decision.

3. What will happen to me if I take part?

I should be most grateful if you could kindly spare your valuable time to complete the accompanying questionnaire. The questionnaire takes a maximum of ten minutes of your time. This questionnaire covers factors that are associated with human reliability in pilotage. This questionnaire will be available for one month from the date of this letter. The researcher will be able to sign into the e-survey to view the results after you have completed the questionnaire. Your valuable feedback will greatly benefit and contribute to the formulation of an industry-wide opinion.

4. Are there any risks/benefits involved?

There are no potential risks involved to the participants in this study and there are no personal benefits resulting from this study.

5. Will my feedback in this study be kept confidential?

Yes. Although I have asked every participant to include his/her email address as mandatory required information, this will be kept highly confidential and not be released by any means. The reason that I have asked experts to include email addresses is that I may need to return questionnaires with feedback for the second round or for up to three rounds (if required) as part of the methodology process. After finalising these rounds, a pairwise comparison will be sent again to the experts through email to assign weight to every criterion. In addition, I am the only person who will handle and secure this information, through changing the settings of the online survey to ensure that the researcher is the only person who can access participants' answers.

This study has received ethical approval from LJMU's Research Ethics Committee (17/MMT/001)

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If you have any concerns regarding your involvement in this research, please discuss these issues with the researcher in the first instance. If you wish to make a complaint, please contact the research ethical team at (researchethics@ljmu.ac.uk) and your communication will be re-directed to an independent person as appropriate.

Delphi Questionnaire

Round One

The development of a marine pilot reliability index (MPRI) within port pilotage operations

- **Please Circle as appropriate:**

Personal Information

1- Name (optional): …………………………………..

2- Nationality: (e.g. British, Singaporean) …………………………………

3- Country of operation: (e.g. UK, Singapore) ……………………………

4- E-mail: …………………………………………..

5- Gender: a) Male b)Female

6- Age Group: (20 – 29) (30 – 39) (40 – 49) (50 – 59) (60 or over)

7- Current Position: (Trainee Pilot) (First Pilot) (Second Pilot) (Third Pilot)

8- Qualification: (Diploma + Pilot Licence) (Third Officer + Pilot Licence) (Second Officer + Pilot Licence) (Chief Officer + Pilot Licence) (Master Mariner + Pilot Licence)

9- Experience as a pilot: (0 – 5 Years) (6 – 10 Years) (11 – 15 Years) (16 – 20 Years) (20 Years and over)

Questionnaire

The aim of this questionnaire is to identify how significant are the different reliability indexes that influence the marine pilot's reliability during the port pilotage operation based on experts' opinions.

It is important to be aware of that, the following identified factors have been selected carefully after an intensive literature review of different disciplines. The links between these factors can be easily observed. For instance, the way that an operator can make an operational decision to proceed with the most optimum solution: this requires higher teamwork efficiency and enough experience in the field, supported by the appropriate training and qualifications that help enhance the operator's situation awareness and reduce the risk of stresses, and so forth. What is behind this questionnaire then is to see the applicability of these selected factors when applied within a marine pilotage operation as a novel method to predict pilotage operation reliability and efficiency.

Therefore, based on your experience, kindly rate the level of significance of the reliability indexes described below to the overall operational reliability within a marine pilotage operation, using the following rating scale:

'1' represents 'Not at all important'

'5' represents 'Extremely important'

After you have carried out the rating, kindly add any comments in the 'comment box' (if you have).

Reliability Index	**Importance scale**				
1. **Technical Proficiency**	Not at all important < ------ > extremely important				
1.1 **Qualification:** A set of competences (educational level, licences and certifications) that exhibit his/her achievement in order to comply with the minimum work-related knowledge required to carry out certain duties.	1	2	3	4	5
Comment:					
1.2 **Specific Training:** A set of compulsory or additional work-related courses and refresher training required to maintain the minimum operational standard.	1	2	3	4	5
Comment:					
1.3 **Working Experience:** The accumulation of knowledge or skills gained over time as a pilot.	1	2	3	4	5
Comment:					

Reliability Index	**Importance scale**				
2. **Personal Fatigue**	Not at all important < ------ > extremely important				
2.1 **Working Hours:** The number of working hours per day or the time of the day when the operator is carrying out his/her duty.	1	2	3	4	5
Comment:					
2.2 **Work Stresses:** Commercial and economic stresses, management stresses, work-related demand, high level of traffic, management style, etc.	1	2	3	4	5
Comment:					
2.3 **Working Environment:** Physical working environment, ergonomic design, the status of the operative's environment.	1	2	3	4	5
Comment:					

Reliability Index	**Importance scale**				
3. Non-Technical Skills	Not at all important < ------ > extremely important				
3.1 Decision-Making: Encompasses a set of structural sequences that includes defining and diagnosing problems, generating options, assessing risks and option selection through different available alternatives, followed by an outcome review.	1	2	3	4	5
Comment:					
3.2 Situation Awareness: Is the perception of elements in the current situation through information gathering, followed by assessing the significance of the gathered information from different resources to form a clear picture to implement a procedure for the current operational event, and finally implement the necessary action to avoid an unfavourable event.	1	2	3	4	5
Comment:					
3.3 Communication Skills: Is the ability of a member to regulate, control, motivate, express feelings and convey information to other team members involved in an operation.	1	2	3	4	5
Comment:					
3.4 Teamwork and Leadership: Is the way to establish a clear two-way channel of communication, openness to criticism, empathy towards cultural diversity, capability to motivate people and develop a community atmosphere, cope with an operator's limitations, and be a key team player.	1	2	3	4	5
Comment:					

Reliability Index	**Importance scale**				
4. Fitness and Strength	Not at all important < ------ > extremely important				
4.1 Operator Age: As an operator gains work-related experience, he/she is getting older. Operator age can indicate how the performance of an experienced operator changes over time. For example, a reduction in physical capacities and coordination, flexibility, strength and power can be expected when getting older.	1	2	3	4	5
Comment:					
4.2 Health Issue: This has been identified as a factor that is strongly associated with accidents at sea. It can be a result of the nature of the work, geographical location, stresses at work, prolonged working hours, commercial pressure and organisational culture as well as historic family illness.	1	2	3	4	5
Comment:					
4.3 Body Strength: Pilots are required to maintain a high level of body strength, as they need to climb a ladder from time to time, this will followed by a high level of cognitive demand required to guide the ship safely during pilotage operations. Any reduction in body strength will affect a pilot's ability to work effectively and limits cognitive ability.	1	2	3	4	5
Comment:					

Thank you for your participation.

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Developing a marine pilot reliability index (MPRI) within port pilotage operations

INVITATION LETTER

Before I start the second round of the Delphi survey, I would like to thank you so much for your participation in the first round; I deeply appreciate your opinion. Certainly, without your valuable opinion and support, this study cannot succeed.

In the first round, I highlighted that this study facilitates a number of questionnaire rounds. The minimum number of rounds required to process the Delphi technique are two. Thus, I really appreciate you assisting me by participating in this second-round questionnaire.

The second questionnaire round summarises the level of importance of each reliability indicator that was given by all the experts in round one. The main objective of this process is to give you, as a participant, the opportunity to reconsider yours answers if you believe it may be better to change them.

The process for the second round begins by aggregating all the experts' results, including yours. Although the results from the first round revealed a consensus state, all comments given by experts have been considered and revised. As a result, there is no additional reliability indicator to be added in the second round.

The statistical results obtained from the first round are presented in this round in the form of three numbers and next, to each reliability indicator, the median (M), inter-quartile range (IQR) and your response (YRes) from the first round. For this research, a greater median indicates greater reliability indicator importance. A lower IQR indicates a higher degree of consensus among the participants.

The developed reliability index (RI) for a marine pilot in this research will assist decision-makers in predicting changes in a pilot's performance, in order to maintain operational efficiency; port management, in order to improve operational standards and procedures; and port authorities, in order to enhance the reliability of the marine pilotage operation. Thus, your valuable opinion and comment will significantly contribute towards developing the reliability index for a marine pilot. I would appreciate it if you could spare me your time and effort, if you agree to participate, in completing the second-round questionnaire. This questionnaire will be available for two weeks, ending on **31 Aug 2017**.

Thank you in advance for your participation, time and support towards the success of this study. Kindly feel free to contact me at the number/e-mail listed below, if you have any questions or problems in regard to this study.

I look forward to hearing from you.

Yours faithfully

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Round Two

The development of a marine pilot reliability index (MPRI) within port pilotage operations

- **Please check your personal information below:**

- **Personal Information**

1- Name :

2- Nationality:

3- Country of operation:

4- E-mail:

5- Gender: Male

6- Age Group: (20 – 29) (30 – 39) (40 – 49) (50 – 59) (60 or over)

7- Current Position: (Trainee Pilot) (First Pilot) (Second Pilot) (Third Pilot)

8- Qualification: (Diploma + Pilot Licence) (Third Officer + Pilot Licence) (Second Officer + Pilot Licence) (Chief Officer + Pilot Licence) (Master Mariner + Pilot Licence)

9- Experience as a pilot: (0 – 5 Years) (6 – 10 Years) (11 – 15 Years) (16 – 20 Years) (20 Years and over)

- **Delphi Questionnaire (round two)**

You have rated each reliability indicator described below in round one. However, if you think it necessary to reconsider your answers from round one, please rate how important you think this particular measure is to the overall level of a pilot's reliability, using the rating scale 1 to 5, where:

'1' represents 'Not at all important'
'5' represents 'Extremely important'

In round two, each reliability indicator is followed by three numbers, comprising the median (M), inter-quartile range (IQR), and your response (YRes) from round one. To achieve the goal of this study, the median score must be equal to 3.75 or more on every reliability indicator criterion in order to consider that the indicator has reached a suitable level of importance. For a reliability indicator to be considered as having reached a suitable level of consensus amongst the expert panel, the inter-quartile range must be 1.00 or less. If any of the reliability indicators meet the above two criteria at the same time, this means that the reliability indicator has reached a suitable level of importance and consensus. Finally, I have presented your response (YRes) score from the first round.

In this questionnaire (the second round), you have been given the chance to reconsider your answer by comparing it to the average rating from other members of the expert panel or to rate it with the same score as you did previously. However, if your response from the previous round is shown to be outside of the median and the IQR resulting from the first round, then your response will highlighted in red. For instance, if the median of a reliability indicator scored 4, the IQR is 1 and your response was 3, then you will see the following: (M = 4, IQR = 1, YRes = 3). If you are still satisfied with your response, despite it being outside the IQR, I would appreciate it if you could comment in the “Comment box” as to why you still consider it as an appropriate choice, despite it remaining outside the consensus range.

Reliability Index	**Importance scale**				
1. Technical Proficiency	Not at all important < ------ > extremely important				
1.1 Qualification: A set of competences (educational level, licences and certifications) that exhibit his/her achievement in order to comply with the minimum work-related knowledge required to carry out certain duties. (M = 4, IQR = 1, YRes =)	1	2	3	4	5
Comment:					
1.2 Specific Training: A set of compulsory or additional work-related courses and refresher training required to maintain the minimum operational standard. (M = 5, IQR = 0, YRes =)	1	2	3	4	5
Comment:					
1.3 Working Experience: The accumulation of knowledge or skills gained over time as a pilot. (M = 5, IQR = 0, YRes =)	1	2	3	4	5
Comment:					

Reliability Index	**Importance scale**				
2. Personal Fatigue	Not at all important < ------ > extremely important				
2.1 Working Hours: The number of working hours per day or the time of the day when the operator is carrying out his/her duty. (M = 4, IQR = 0, YRes =)	1	2	3	4	5
Comment:					
2.2 Work Stresses: Commercial and economic stresses, management stresses, work-related demand, high level of traffic, management style, etc. (M = 4, IQR = 0, YRes =)	1	2	3	4	5
Comment:					
2.3 Working Environment: Physical working environment, ergonomic design, the status of the operative’s environment. (M = 4, IQR = 0, YRes =)	1	2	3	4	5
Comment:					

Reliability Index	**Importance scale**				
3. Non-Technical Skills	Not at all important < ------ > extremely important				
3.1 Decision-Making: Encompasses a set of structural sequences that includes defining and diagnosing problems, generating options, assessing risks and option selection through different available alternatives, followed by an outcome review. (M = 5, IQR = 0, YRes =)	1	2	3	4	5
Comment:					
3.2 Situation Awareness: Is the perception of elements in the current situation through information gathering, followed by assessing the significance of the gathered information from different resources to form a clear picture to implement a procedure for the current operational event, and finally implement the necessary action to avoid an unfavourable event. (M = 4, IQR = 0, YRes =)	1	2	3	4	5
Comment:					
3.3 Communication Skills: Is the ability of a member to regulate, control, motivate, express feelings and convey information to other team members involved in an operation. (M = 4, IQR = 0, YRes =)	1	2	3	4	5
Comment:					
3.4 Teamwork and Leadership: Is the way to establish a clear two-way channel of communication, openness to criticism, empathy towards cultural diversity, capability to motivate people and develop a community atmosphere, cope with an operator's limitations, and be a key team player. (M = 4, IQR = 0, YRes =)	1	2	3	4	5
Comment:					

Reliability Index	**Importance scale**				
4. Fitness and Strength	Not at all important < ------ > extremely important				
4.1 Operator Age: As an operator gains work-related experience, he/she is getting older. Operator age can indicate how the performance of an experienced operator changes over time. For example, a reduction in physical capacities and coordination, flexibility, strength and power can be expected when getting older. (M = 4, IQR = 1, YRes =)	1	2	3	4	5
Comment:					
4.2 Health Issue: This has been identified as a factor that is strongly associated with accidents at sea. It can be a result of the nature of the work, geographical location, stresses at work, prolonged working hours, commercial pressure and organisational culture as well as historic family illness. (M = 4, IQR = 0, YRes =)	1	2	3	4	5
Comment:					
4.3 Body Strength: Pilots are required to maintain a high level of body strength, as they need to climb a ladder from time to time, this will followed by a high level of cognitive demand required to guide the ship safely during pilotage operations. Any reduction in body strength will affect a pilot's ability to work effectively and limits cognitive ability. (M = 4, IQR = 1, YRes =)	1	2	3	4	5
Comment:					

Thank you for your participation.

Analytical Hierarchy Process (AHP) Questionnaire

In order to assess the marine pilotage service, weights assignment to each key players involved into the operation and for each marine pilot reliability index (MPRIs) plays an important role in the context of the assessment process.

A critical characteristic of the AHP is the consistency of the answers obtained by a pairwise comparison. If the value of the CR showing of 0.10 or less, this confirms an acceptable level of expert's judgement consistency. For your better understanding, the following is an example in how to conduct the survey.

Example

Part 1: Group A: If you think the first criterion, **Marine Pilot** is strongly important on influencing the Pilotage Operation Reliability than the second criterion **Ship Master**, and Tug Master is strongly important than the Marine Pilot, then the Tug Master is more important than the Ship Master, this can be tick as follows:

Pairwise comparison																		
Criterion	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**Criterion**
Pilot	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Ship Master
Pilot	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Tug Master
Ship Master	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Tug Master

NB: Please remember to **mark only one number on either the left or right side** of the scale of importance or just the middle of the scale which is equal importance.

PART A: Weight assignments for main pilotage components

For marine pilotage operation, there are five main key players involved into the operation: *marine pilot (MP), ship master (SM), tug master (TM), vessel traffic service operator (VTS), and harbor master (HM)*. Please estimate its relative importance of each key players by following the pairwise comparison technique as illustrated above.

Pairwise comparison																		
Criterion	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**Criterion**
MP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SM
MP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	TM
MP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	VTS
MP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HM
SM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	TM
SM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	VTS
SM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	TM
TM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	VTS
TM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HM
VTS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HM

PART B: Weight assignments for the main criteria of Marine Pilot Reliability Index (MPRI)

For marine pilot reliability index (MPRI), there are FOUR main sub-criteria play significantly on shaping pilot's reliability: *technical proficiency (TP), personal fatigue (PF), non-technical skills (NTS), and fitness & strength (F&S)*. Please estimate its relative importance of each MPRI's by following the pairwise comparison technique similar as above.

Pairwise comparison																		
MPRI	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI**
TP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PF
TP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NTS
TP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	F&S
PF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NTS
PF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	F&S
NTS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	F&S

PART C: Weight assignments for the lower criteria of Marine Pilot Reliability Index (MPRI)

1- For marine pilot reliability index (MPRI), Technical Proficiency (TP) is the first main criterion of in the MPRI. TP has three sub criteria: *qualification and pilotage licensing (QPL), special training (ST), and working experience (WEx)*. Please estimate its relative importance of each MPRI's by following the pairwise comparison technique similar as above.

Pairwise comparison																		
MPRI	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI**
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ST
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx
ST	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx

2- For marine pilot reliability index (MPRI), Personal Fatigue (PF) is the second main criterion of in the MPRI. PF has three sub criteria: *working hours (WH), work stresses (WS), and working environment (WEnv)*. Please estimate its relative importance of each MPRI's by following the pairwise comparison technique similar as above.

Pairwise comparison																		
MPRI	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI**
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WS
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv
WS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv

3- For marine pilot reliability index (MPRI), Non-Technical Skills (NTS) is the third main criterion of in the MPRI. NTS has four sub criteria: *decision-making skills (DM), situation awareness skill (SA), communication skill (CS), and teamwork & leadership skills (T&L)*. Please estimate its relative importance of each MPRI's by following the pairwise comparison technique similar as above.

Pairwise comparison																		
MPRI	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

4- For marine pilot reliability index (MPRI), Fitness & Strength (F&S) is the fourth main criterion of in the MPRI. F&S has three sub criteria: *operator age (OA), health issue (HI), and body strength (BS)*. Please estimate its relative importance of each MPRI's by following the pairwise comparison technique similar as above.

Pairwise comparison																		
MPRI	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI**
OA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HI
OA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	BS
HI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	BS

THANK YOU VERY MUCH FOR YOUR PARTICIPATION

FDEMATEL Questionnaire

Interdependency evaluation on main four MPRIs Dimensions

The following evaluations based on influence comparisons, kindly, based on your experience, use the following 5-linguistic scale to estimate to what extent each Dimension (A) affects Dimension (B); where:

(0) NO Influence
(1) Low Influence
(2) Medium Influence
(3) High Influence
(4) Very High Influence

This part aims to evaluate the causal relationships among the main four dimensions constituting the MPRI evaluation and selection framework (Technical Proficiency, Personal Fatigue, Non-Technical Skills, and Fitness & Strength)

- **Technical Proficiency (TP)** includes qualifications and pilotage licensing **(TP-QPL)**, special training **(TP-ST)**, and working experience **(TP-WEx)**.
- **Personal Fatigue (PF)** includes working hours **(PF-WH)**, work stresses **(PF-WS)**, and working environment **(PF-WEnv)**.
- **Non-Technical skills (NTS)** include Decision-making skills **(NTS-DM)**, situation awareness skills **(NTS-SA)**, communication skills **(NTS-CS)**, and teamwork & leadership skills **(NTS-T&L)**.
- **Fitness & Strength (F&S)** includes operator age **(F&S-OA)**, health issues **(F&S-HI)**, and body strength **(F&S-BS)**.

Influence Comparisons						
Dimension (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Dimension (B)**
TP						HF
TP						NTS
TP						F&S
PF						TP
PF						NTS
PF						F&S
NTS						TP
NTS						HF
NTS						F&S
F&S						TP
F&S						HF
F&S						NTS

- **Interdependency evaluation on main 13 sub MPRIs main dimensions**

Based on the causal relationships between the main four dimensions, this part aims to evaluate the causal relationships among the sub-main dimensions identified above that constituting the MPRI evaluation and selection framework.

Similarly, the following evaluations based on pairwise comparisons, kindly, based on your experience, use the following 5-linguistic scale to estimate to what extent each Indicator (A) affects Indicator (B); where:

(0) NO Influence
(1) Low Influence
(2) Medium Influence
(3) High Influence
(4) Very High Influence

Influence Comparisons						
Indicator (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Indicator (B)**
TP-QPL						PF-WS
TP-QPL						PF-WEnv
TP-QPL						NTS-DM
TP-QPL						NTS-SA
TP-QPL						NTS-CS
TP-QPL						NTS-T&L

(**TP-QPL**: Technical Proficiency-Qualification and Pilotage Licensing; **PF-WH**: Personal Fatigue-Working Hours; **PF-WS**: Personal Fatigue-Work Stresses; **PF-WEnv**: Personal Fatigue-Working Environment; **NTS-DC**: Non-Technical Skills-Decision-Making skills; **NTS-SA**: Non-Technical Skills-Situation Awareness: **NTS-CS**: Non-Technical Skills-Communication skills; **NTS-T&L**: Non-Technical Skills-Teamwork and Leadership skills).

Influence Comparisons						
Indicator (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Indicator (B)**
TP-ST						PF-WH
TP-ST						PF-WS
TP-ST						PF-WEnv
TP-ST						NTS-DM
TP-ST						NTS-SA
TP-ST						NTS-CS
TP-ST						NTS-T&L

(**TP-ST**: Technical Proficiency-Special Training; **PF-WH**: Personal Fatigue-Working Hours; **PF-WS**: Personal Fatigue-Work Stresses; **PF-WEnv**: Personal Fatigue-Working Environment; **NTS-DC**: Non-Technical Skills-Decision-Making skills; **NTS-SA**: Non-Technical Skills-Situation Awareness: **NTS-CS**: Non-Technical Skills-Communication skills; **NTS-T&L**: Non-Technical Skills-Teamwork and Leadership skills).

Influence Comparisons						
Indicator (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Indicator (B)**
TP-WEx						PF-WH
TP-WEx						PF-WS
TP-WEx						PF-WEnv
TP-WEx						NTS-DM
TP-WEx						NTS-SA
TP-WEx						NTS-CS
TP-WEx						NTS-T&L

(**TP-WEx**: Technical Proficiency-Working Experience; **PF-WH**: Personal Fatigue-Working Hours; **PF-WS**: Personal Fatigue-Work Stresses; **PF-WEnv**: Personal Fatigue-Working Environment; **NTS-DC**: Non-Technical Skills-Decision-Making skills; **NTS-SA**: Non-Technical Skills-Situation Awareness: **NTS-CS**: Non-Technical Skills-Communication skills; **NTS-T&L**: Non-Technical Skills-Teamwork and Leadership skills).

Influence Comparisons						
Indicator (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Indicator (B)**
PF-WH						TP-WEx
PF-WH						NTS-DM
PF-WH						NTS-SA
PF-WH						NTS-CS
PF-WH						NTS-T&L
PF-WH						F&S-OA
PF-WH						F&S-HI
PF-WH						F&S-BS

(**TP-QPL**: Technical Proficiency-Qualification and Pilotage Licensing; **TP-ST**: Technical Proficiency-Special Training; **TP-WEx**: Technical Proficiency-Working Experience; **NTS-DC**: Non-Technical Skills-Decision-Making skills; **NTS-SA**: Non-Technical Skills-Situation Awareness: **NTS-CS**: Non-Technical Skills-Communication skills; **NTS-T&L**: Non-Technical Skills-Teamwork and Leadership skills; **F&S-OA**: Fitness and Strength-Operator Age; **F&S-HI**; Fitness and Strength-Health Issue; **F&S-BS**: Fitness and Strength-Body Strength).

Influence Comparisons						
Indicator (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Indicator (B)**
PF-WS						TP-WEx
PF-WS						NTS-DM
PF-WS						NTS-SA
PF-WS						NTS-CS
PF-WS						NTS-T&L
PF-WS						F&S-HI
PF-WS						F&S-BS

(**TP-QPL**: Technical Proficiency-Qualification and Pilotage Licensing; **TP-ST**: Technical Proficiency-Special Training; **TP-WEx**: Technical Proficiency-Working Experience; **PF-WS**: Personal Fatigue-Work Stresses; **NTS-DC**: Non-Technical Skills-Decision-Making skills; **NTS-SA**: Non-Technical Skills-Situation Awareness: **NTS-CS**: Non-Technical Skills-Communication skills; **NTS-T&L**: Non-Technical Skills-Teamwork and Leadership skills; **F&S-OA**: Fitness and Strength-Operator Age; **F&S-HI**: Fitness and Strength-Health Issue; **F&S-BS**: Fitness and Strength-Body Strength).

Influence Comparisons						
Indicator (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Indicator (B)**
PF-WEnv						TP-QPL
PF-WEnv						TP-ST
PF-WEnv						TP-WEx
PF-WEnv						NTS-DM
PF-WEnv						NTS-SA
PF-WEnv						NTS-CS
PF-WEnv						NTS-T&L
PF-WEnv						F&S-HI
PF-WEnv						F&S-BS

(**TP-QPL**: Technical Proficiency-Qualification and Pilotage Licensing; **TP-ST**: Technical Proficiency-Special Training; **TP-WEx**: Technical Proficiency-Working Experience; **PF-WEnv**: Personal Fatigue-Working Environment; **NTS-DC**: Non-Technical Skills-Decision-Making skills; **NTS-SA**: Non-Technical Skills-Situation Awareness: **NTS-CS**: Non-Technical Skills-Communication skills; **NTS-T&L**: Non-Technical Skills-Teamwork and Leadership skills; **F&S-OA**: Fitness and Strength-Operator Age; **F&S-HI**: Fitness and Strength-Health Issue; **F&S-BS**: Fitness and Strength-Body Strength).

Influence Comparisons						
Indicator (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Indicator (B)**
F&S-OA						TP-QPL
F&S-OA						TP-ST
F&S-OA						TP-WEx
F&S-OA						PF-WH
F&S-OA						PF-WS
F&S-OA						PF-WEnv
F&S-OA						NTS-DM
F&S-OA						NTS-SA
F&S-OA						NTS-CS
F&S-OA						NTS-T&L

(**TP-QPL**: Technical Proficiency-Qualification and Pilotage Licensing; **TP-ST**: Technical Proficiency-Special Training; **TP-WEx**: Technical Proficiency-Working Experience; **PF-WH**: Personal Fatigue-Working Hours; **PF-WS**: Personal Fatigue-Work Stresses; **PF-WEnv**: Personal Fatigue-Working Environment; **NTS-DC**: Non-Technical Skills-Decision-Making skills; **NTS-SA**: Non-Technical Skills-Situation Awareness: **NTS-CS**: Non-Technical Skills-Communication skills; **NTS-T&L**: Non-Technical Skills-Teamwork and Leadership skills; **F&S-OA**: Fitness and Strength-Operator Age).

Influence Comparisons						
Indicator (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Indicator (B)**
F&S-HI						TP-QPL
F&S-HI						TP-ST
F&S-HI						TP-WEx
F&S-HI						PF-WH
F&S-HI						PF-WS
F&S-HI						PF-WEnv
F&S-HI						NTS-DM
F&S-HI						NTS-SA
F&S-HI						NTS-CS
F&S-HI						NTS-T&L

(**TP-QPL**: Technical Proficiency-Qualification and Pilotage Licensing; **TP-ST**: Technical Proficiency-Special Training; **TP-WEx**: Technical Proficiency-Working Experience; **PF-WH**: Personal Fatigue-Working Hours; **PF-WS**: Personal Fatigue-Work Stresses; **PF-WEnv**: Personal Fatigue-Working Environment; **NTS-DC**: Non-Technical Skills-Decision-Making skills; **NTS-SA**: Non-Technical Skills-Situation Awareness: **NTS-CS**: Non-Technical Skills-Communication skills; **NTS-T&L**: Non-Technical Skills-Teamwork and Leadership skills; **F&S-HI**: Fitness and Strength-Health Issue).

Influence Comparisons						
Indicator (A)	**NO Influence**	**Low Influence**	**Medium Influence**	**High Influence**	**V. High Influence**	**Indicator (B)**
F&S-BS						TP-QPL
F&S-BS						TP-ST
F&S-BS						TP-WEx
F&S-BS						PF-WH
F&S-BS						PF-WS
F&S-BS						PF-WEnv
F&S-BS						NTS-DM
F&S-BS						NTS-SA
F&S-BS						NTS-CS
F&S-BS						NTS-T&L

(**TP-QPL**: Technical Proficiency-Qualification and Pilotage Licensing; **TP-ST**: Technical Proficiency-Special Training; **TP-WEx**: Technical Proficiency-Working Experience; **PF-WH**: Personal Fatigue-Working Hours; **PF-WS**: Personal Fatigue-Work Stresses; **PF-WEnv**: Personal Fatigue-Working Environment; **NTS-DC**: Non-Technical Skills-Decision-Making skills; **NTS-SA**: Non-Technical Skills-Situation Awareness: **NTS-CS**: Non-Technical Skills-Communication skills; **NTS-T&L**: Non-Technical Skills-Teamwork and Leadership skills; **F&S-BS**: Fitness and Strength-Body Strength).

Thank you for your participation

Analytical Network Process (ANP)

Interdependent weights assignment

Part A: Weights assignment (main 4 Dimensions)

There are 4 dimensions that influence a marine pilot's reliability were identified: technical proficiency (TP), personal fatigue (PF), non-technical skills (NTS) and fitness & strength (F&S). Kindly, based on your opinion, estimate the relative importance of each dimension through the following pairwise matrices.

1- Which dimension influences 'Technical Proficiency TP' more: 'dimension A' or 'dimension B'? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
PF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NTS

(**PF:** Personal Fatigue; **NTS:** Non-Technical Skills)

2- Which dimension influences 'Personal Fatigue PF' more: 'dimension A' or 'dimension B'? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
TP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NTS
TP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	F&S
NTS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	F&S

(**TP:** Technical Proficiency; **NTS:** Non-Technical Skills; **F&S:** Fitness and Strength)

3- Which dimension influences 'Fitness & Strength F&S' more: 'dimension A' or 'dimension B'? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
TP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	PF
TP	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NTS
PF	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NTS

(**TP:** Technical Proficiency; **PF:** Personal Fatigue; **NTS:** Non-Technical Skills)

Part B: Weights assignment for the 13 MPRIs indicators

1. With respect to the indicator qualification and pilotage licensing (QPL), which MPRI's influences 'QPL' more: 'indicator A', or 'indicator B'? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
WS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv

(**WS**: Work Stresses; **WEnv**: Working Environment)

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

(**DC**: Decision-Making skills; **SA**: Situation Awareness skills: **CS**: Communication skills; **T&L**: Teamwork and Leadership skills)

2. With respect to the indicator 'special training (ST)', which MPRI's influences 'output ST' more: 'indicator A', or 'indicator B'? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WS
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv
WS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv

(**WH**: Working Hours**; WS**: Work Stresses; **WEnv**: Working Environment)

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

(**DC**: Decision-Making skills; **SA**: Situation Awareness skills: **CS**: Communication skills; **T&L**: Teamwork and Leadership skills)

3. With respect to the indicator 'working experience (WEx)', which principal MPRI influences 'output WEx' more: 'indicator A', or 'indicator B'? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WS
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv
WS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv

(**WH**: Working Hours**; WS**: Work Stresses; **WEnv**: Working Environment)

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

(**DC**: Decision-Making skills; **SA**: Situation Awareness skills: **CS**: Communication skills; **T&L**: Teamwork and Leadership skills)

4. With respect to the indicator ‘working hours (WH)’, which MPRI’s influences ‘output WH’ more: ‘indicator A’, or ‘indicator B’? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

(**DC**: Decision-Making skills; **SA**: Situation Awareness skills: **CS**: Communication skills; **T&L**: Teamwork and Leadership skills)

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
OA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	HI
OA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	BS
HI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	BS

(**OA**: Operator Age**; HI**: Health Issue; **BS**: Body Strength)

5. With respect to output (WS), which principal MPRI influences ‘output WS’ more: ‘indicator A’, or ‘indicator B’? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

(**DC**: Decision-Making skills; **SA**: Situation Awareness skills: **CS**: Communication skills; **T&L**: Teamwork and Leadership skills)

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
HI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	BS

(**HI**: Health Issue; **BS**: Body Strength)

6. With respect to the indicator ‘working environment (WEnv)’, which MPRI’s influences ‘output WEnv’ more: ‘indicator A’, or ‘indicator B’? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ST
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx
ST	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx

(**QPL**: Qualification and Pilotage Licensing**; ST**: Special Training; **WEx**: Working Experience)

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

(**DC**: Decision-Making skills; **SA**: Situation Awareness skills: **CS**: Communication skills; **T&L**: Teamwork and Leadership skills)

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
HI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	BS

(**HI**: Health Issue; **BS**: Body Strength)

7. With respect to the indicator ‘operator age (OA)’, which MPRI’s influences ‘output OA’ more: ‘indicator A’, or ‘indicator B’? and how much more?

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ST
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx
ST	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx

(**QPL**: Qualification and Pilotage Licensing**; ST**: Special Training; **WEx**: Working Experience)

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WS
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv
WS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv

(**WH**: Working Hours**; WS**: Work Stresses; **WEnv**: Working Environment)

Pairwise comparison																		
MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

(**DC**: Decision-Making skills; **SA**: Situation Awareness skills: **CS**: Communication skills; **T&L**: Teamwork and Leadership skills)

8. With respect to the indicator ‘health issue (HI)’, which MPRI’s influences ‘output HI’ more: ‘indicator A’, or ‘indicator B’? and how much more?

Pairwise comparison

MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ST
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx
ST	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx

(**QPL**: Qualification and Pilotage Licensing**; ST**: Special Training; **WEx**: Working Experience)

Pairwise comparison

MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WS
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv
WS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv

(**WH**: Working Hours**; WS**: Work Stresses; **WEnv**: Working Environment)

Pairwise comparison

MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

(**DC**: Decision-Making skills; **SA**: Situation Awareness skills: **CS**: Communication skills; **T&L**: Teamwork and Leadership skills)

9. With respect to the indicator ‘body strength (BS)’, which MPRI’s influences ‘output BS’ more: ‘indicator A’, or ‘indicator B’? and how much more?

Pairwise comparison

MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	ST
QPL	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx
ST	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEx

(**QPL**: Qualification and Pilotage Licensing**; ST**: Special Training; **WEx**: Working Experience)

Pairwise comparison

MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WS
WH	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv
WS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	WEnv

(**WH**: Working Hours**; WS**: Work Stresses; **WEnv**: Working Environment)

Pairwise comparison

MPRI (A)	**High**			**Average**			**Low**		**equal**	**Low**		**Average**			**High**			**MPRI (B)**
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	SA
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
DM	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	CS
SA	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L
CS	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	T&L

(**DC**: Decision-Making skills; **SA**: Situation Awareness skills: **CS**: Communication skills; **T&L**: Teamwork and Leadership skills)

Thank you for your participation

Appendix II the application process of FER approach

II.1 Pilot 1

II.1.1 Aggregation process of MPRIs

The synthesis of Pilot 1's personal fatigue sub-criterion using the ER algorithms has been demonstrated on section 6.4.6.1. In the following section, the aggregation process for the remaining lower criterion towards the main goal were described.

II.1.1 Technical Proficiency (TP)

The following is the aggregation process of pilot’s 1 TP, in relation to the sub-criteria of qualification and pilotage licensing (QPL), special training (ST), and working experience (WEx), based on the information given by Pilot 1. Using ER equations can applied as follows:

Aggregating Pilot’s 1 TP Sub-Criteria $\widetilde{\mathrm{TP}}_{\mathrm{QPL}}$, $\widetilde{\mathrm{TP}}_{\mathrm{ST}}$, and $\widetilde{\mathrm{TP}}_{\mathrm{WEx}}$ using ER algorithms, we need to define the following:

$\widetilde{\mathrm{TP}}_{\mathrm{QPL}}$, which represents the sub-criterion Qualification and Pilotage Licensing (QPL);

$\widetilde{\mathrm{TP}}_{\mathrm{ST}}$, which represents the sub-criterion Special Training (ST);

$\widetilde{\mathrm{TP}}_{\mathrm{WEx}}$, which represents the sub-criterion Working Experience (WEx).

Based on the given fuzzy information of QPL, ST, and WEx for Pilot 1, the results from the mapping process are as follows:

$R\widetilde{\mathrm{TP}}_{\mathrm{QPL}}$ = {(V. Good, 0.36), (Good, 0.64), (Average, 0), (Low, 0), (Basic, 0)}

$R\widetilde{\mathrm{TP}}_{\mathrm{ST}}$= {(V. Good, 0), (Good, 0.2), (Average, 0.8), (Low, 0), (Basic, 0)}

$R\widetilde{\mathrm{TP}}_{\mathrm{WEx}}$= {(V. Good, 0), (Good, 0.04), (Average, 0.24), (Low, 0.72), (Basic, 0)}

The global weights obtained by ANP are as follows:

ω_{QPL}= 0.004, ω_{ST}= 0.013, and ω_{WEx}= 0.028

Where:

ω_{QPL}, is the global weight assigned for TP-QPL;

ω_{ST}, is the global weight assigned for TP-ST;

ω_{WEx}, represents the global weight assigned for TP-WEx.

Since the weights' sums are not equal to 1, they must be normalised. To normalise the weight for each criterion, divide the weight of each criterion to the sum of all criteria. The sum of QPL, ST, and WEx are as follows:

$\omega_{QPL} + \omega_{ST} + \omega_{WEx} =$ 0.004+ 0.013+ 0.028= 0.045.

A normalised ω_{QPL}= 0.004/0.045= 0.089.

Similarly, ω_{ST}= 0.289 and ω_{WEx}= 0.622

The aggregation process of the first two criterion of TP, TP_{QPL} and $\widetilde{TP}_{ST}$, are as follows:

M_1^mrepresents the subset $\widetilde{TP}_{QPL}$, and M_2^m represent the subset $\widetilde{TP}_{ST}$. Using ER equation (6.4), can obtain the followings:

$M_1^m = \omega_{QPL}\beta_1^m$, where ($m$ = 1,2,3,4,5)

$M_2^m = \omega_{ST}\beta_2^m$, where ($m$ = 1,2,3,4,5)

As a result, the following table has been constructed:

When, m= 1, M_1^1= 0.089×0.36= 0.032, M_2^1= 0.289×0= 0

m= 2, M_1^2= 0.089×0.64 = 0.057, M_2^2= 0.289×0.20= 0.058

m= 3, M_1^3= 0.089×0= 0, M_2^3= 0.289×0.80= 0.0231

m= 4, M_1^4= 0.089×0= 0, M_2^4= 0.289×0= 0

m= 5, M_1^5= 0.089×0= 0, M_2^5= 0.289×0= 0

When $M_{H_{QPL}}$ represents the individual remaining belief for $\mathrm{M}_1^{\mathrm{m}}$, and $M_{H_{ST}}$ represents the individual remaining belief for $\mathrm{M}_2^{\mathrm{m}}$, therefore, equation 6.5, can be applied as follows:

- $M_{H_{QPL}} = \bar{M}_{H_{QPL}} + \widetilde{M}_{H_{QPL}}$

- $M_{H_{ST}} = \bar{M}_{H_{ST}} + \tilde{M}_{H_{ST}}$

$\bar{M}_{H_{QPL}}, \tilde{M}_{H_{QPL}}$, and $\bar{M}_{H_{ST}}\tilde{M}_{H_{ST}}$ can be found by applying equations (6.6-6.7), as follow:

- $\bar{M}_{H_{QPL}} = 1 - \omega_{QPL}$ =1- 0.089 = 0.911
- $\bar{M}_{H_{ST}} = 1 - \omega_{ST}$ =1- 0.289 = 0.711
- $\tilde{M}_{H_{QPL}} = \omega_{WQPL}(1 - \sum_{m}^{5} \beta_1^m)$ = 0.911× (1- (0.36+0.64+0+0+0)) = 0
- $\tilde{M}_{H_{ST}} = \omega_{ST}(1 - \sum_{m}^{5} \beta_2^m)$ = 0.711× (1- (0+0.04+0.24+0.72+0)) = 0
- $M_{H_{QPL}} = \bar{M}_{H_{QPL}} + \tilde{M}_{H_{QPL}}$ = 0.911+0= 0.911
- $M_{H_{ST}} = \bar{M}_{H_{ST}} + \tilde{M}_{H_{ST}}$ = 0.711+0= 0.711

By using equations (6.8-6.11), to find $\beta^{m'} = k\left(M_1^m M_2^m + M_1^m M_{H_{ST}} + M_2^m M_{H_{QPL}}\right)^{-1}$, $(\bar{M}'_{H_U})$, and $(\tilde{M}'_{H_U})$, first we need to find k using equation (6.8):

$k = [1 - \sum_{T=1}^{5} \sum_{R=1 \neq T}^{5} M_1^T M_2^R]^{-1}$

$$k = \left(1 - \begin{array}{ccccc} - + & M_1^1 M_2^2 + & M_1^1 M_2^3 + & M_1^1 M_2^4 + & M_1^1 M_2^5 + \\ M_1^2 M_2^1 + & - + & M_1^2 M_2^3 + & M_1^2 M_2^4 + & M_1^2 M_2^5 + \\ M_1^3 M_2^1 + & M_1^3 M_2^2 + & - + & M_1^3 M_2^4 + & M_1^3 M_2^5 + \\ M_1^4 M_2^1 + & M_1^4 M_2^2 + & M_1^4 M_2^3 + & - + & M_1^4 M_2^5 + \\ M_1^5 M_2^1 + & M_1^5 M_2^2 + & M_1^5 M_2^3 + & M_1^5 M_2^4 + & - \end{array} \right)^{-1}$$

$$k = \big(1 - (- + (0.032 \times 0.058) + (0.032 \times 0.231) + (0.032 \times 0) + (0.032 \times 0) + (0.057 \times 0) + - + (0.057 \times 0.231) + (0.057 \times 0) + (0.057 \times 0) + (0 \times 0) + (0 \times 0.058) + - + (0 \times 0) + (0 \times 0) + (0 \times 0) + (0 \times 0.058) + (0 \times 0.231) + - + (0 \times 0) + (0 \times 0) + (0 \times 0.058) + (0 \times 0.231) + (0 \times 0) + -)\big)^{-1}$$

$$k = \left(1 - \begin{array}{ccccc} - + & 0.002 + & 0.007 + & 0 + & 0 + \\ 0 + & - + & 0.013 + & 0 + & 0 + \\ 0 + & 0 + & - + & 0 + & 0 + \\ 0 + & 0 + & 0 + & - + & 0 + \\ 0 + & 0 + & 0 + & 0 + & - \end{array} \right)^{-1}$$

k= 1.023

Then, before using equations (6.12-6.13) to find (β^{m}) and (M_{H_U}), we need to utilise equations (6.8-6.11), to find ($\beta^{m'}$), ($\bar{M}'_{H_U}$), and ($\tilde{M}'_{H_U}$), as follow:

$\bar{M}'_{H_U} = K(\bar{M}_{H_{QPL}}\bar{M}_{H_{ST}})$ = 1.023× 0.911× 0.711= 0.663

$\tilde{M}'_{H_U} = K(\tilde{M}_{H_{QPL}}\tilde{M}_{H_{ST}} + \tilde{M}_{QPL}\bar{M}_{H_{ST}} + \bar{M}_{H_{QPL}}\tilde{M}_{H_{ST}})$ =

1.023×[(0×0)+(0.911×0)+(0×0.711)]=0

Accordingly, when $\beta^{m} = \frac{\beta^{m'}}{(1-\bar{H}_U)}$ $, where\ (m = 1,2,3,4,5)$, then:

$\beta^{m'} = k\left(M_1^m M_2^m + M_1^m M_{H_{ST}} + M_2^m M_{H_{QPL}}\right)$

$\beta^{1'} = k\left(M_1^1 M_2^1 + M_1^1 M_{H_{ST}} + M_2^1 M_{H_{QPL}}\right) =$

1.023×[(0.032×0)+(0.032×0.711)+(0.911×0)]= 0.023

$\beta^{2'} = k\left(M_1^2 M_2^2 + M_1^2 M_{H_{ST}} + M_2^2 M_{H_{QPL}}\right) =$

1.023×[(0.057×0.058)+(0.057×0.711)+(0.911×0.058)] = 0.099

$\beta^{3'} = k\left(M_1^3 M_2^3 + M_1^3 M_{H_{ST}} + M_2^3 M_{H_{QPL}}\right) =$

1.023×[(0×0.231)+(0×0.711)+(0.911×0.231)] = 0.215

$\beta^{4'} = k\left(M_1^4 M_2^4 + M_1^4 M_{H_{ST}} + M_2^4 M_{H_{QPL}}\right)$ = 1.023×[(0×0)+(0×0.711)+(0.911×0)]= 0

$\beta^{5'} = k\left(M_1^5 M_2^5 + M_1^5 M_{H_{ST}} + M_2^5 M_{H_{QPL}}\right)$ = 1.023×[(0×0)+(0×0.711)+(0.911×0)]= 0

From the above aggregations, the obtained results $\beta^{1'}$, $\beta^{2'}$,$\beta^{3'}$,$\beta^{4'}$, and $\beta^{5'}$represent M_{12}^1, M_{12}^2, M_{12}^3, M_{12}^4, and $M_{12}^5$for the first two aggregations. These will be used with the third aggregation similar to the above aggregation process. The following are the aggregation of the criterion WEx with the aggregated result from QPL and ST:

M_{12}^m represents the aggregated subset of $\widetilde{TP}_{QPL}$, and $\widetilde{TP}_{ST}$, while M_3^m represents the subset $\widetilde{TP}_{WEx}$. Using the ER equation (6.6) can obtain the following:

$M_3^m = \omega_{WEx}\beta_3^m$,   where ($m$ = 1,2,3,4,5)

When, m= 1, M_{12}^{1}= 0.023, M_{3}^{1}= 0.622×0= 0

m= 2, M_{12}^{2}= 0.099, M_{3}^{2}= 0.622×0.04= 0.025

m= 3, M_{12}^{3}= 0.215, M_{3}^{3}= 0.622×0.24= 0.149

m= 4, M_{12}^{4}= 0, M_{3}^{4}= 0.622×0.72= 0.448

m= 5, M_{12}^{5}= 0, M_{3}^{5}= 0.622×0= 0

When $M_{H_{12}}$ represents the individual remaining belief for $\mathrm{M}_{12}^{\mathrm{m}}$, and $M_{H_{WEx}}$ represents the individual remaining belief for $\mathrm{M}_{3}^{\mathrm{m}}$, equation 6.7 can be applied as follows:

- $M_{H_{WEx}} = \overline{M}_{H_{WEx}} + \widetilde{M}_{H_{WEx}}$

$\overline{M}_{H_{WEx}}, \widetilde{M}_{H_{WEx}}$ can be found by applying equations (6.8-6.9) as follows:

- $\overline{M}_{H_{WEx}} = 1 - \omega_{WEx}$ = 1-0.622= 0.378
- $\widetilde{M}_{H_{WEx}} = \omega_{WEx}(1 - \sum_{m}^{5} \beta_{3}^{m})$ = 0.378× (1- (0+0.04+0.24+0.72+0))= 0
- $M_{H_{WEx}} = \overline{M}_{H_{WEx}} + \widetilde{M}_{H_{WEx}}$ = 0.378+0= 0.378

By using equations (6.10-6.13) to find $\beta^{m'} = k\left(M_{12}^{m}M_{3}^{m} + M_{12}^{m}M_{H_{WEx}} + M_{3}^{m}M_{H_{12}}\right)^{-1}$, $(\overline{M}'_{H_U})$, and $(\widetilde{M}'_{H_U})$, we find k using equation (6.13):

$$k = [1 - \textstyle\sum_{T=1}^{5}\sum_{R=1 \neq T}^{5} M_{12}^{T}M_{3}^{R}]^{-1}$$

$$k = \left(1 - \begin{array}{ccccc} -+ & M_{12}^{1}M_{3}^{2}+ & M_{12}^{1}M_{3}^{3}+ & M_{12}^{1}M_{3}^{4}+ & M_{12}^{1}M_{3}^{5}+ \\ M_{12}^{2}M_{3}^{1}+ & -+ & M_{12}^{2}M_{3}^{3}+ & M_{12}^{2}M_{3}^{4}+ & M_{12}^{2}M_{3}^{5}+ \\ M_{12}^{3}M_{3}^{1}+ & M_{12}^{3}M_{3}^{2}+ & -+ & M_{12}^{3}M_{3}^{4}+ & M_{12}^{3}M_{3}^{5}+ \\ M_{12}^{4}M_{3}^{1}+ & M_{12}^{4}M_{3}^{2}+ & M_{12}^{4}M_{3}^{3}+ & -+ & M_{12}^{4}M_{3}^{5}+ \\ M_{12}^{5}M_{3}^{1}+ & M_{12}^{5}M_{3}^{2}+ & M_{12}^{5}M_{3}^{3}+ & M_{12}^{5}M_{3}^{4}+ & - \end{array}\right)^{-1}$$

$$\begin{aligned}
k = \quad & \big(1 - (- + (0.023 \times 0.025) + (0.023 \times 0.149) + (0.023 \times 0.448) + (0.023 \times \\
& 0) + (0.099 \times 0) + - + (0.099 \times 0.149) + (0.099 \times 0.448) + (0.099 \times 0) + \\
& (0.215 \times 0) + (0.215 \times 0.025) + - + (0.215 \times 0.448) + (0.215 \times 0) + (0 \times 0) + \\
& (0 \times 0.025) + (0 \times 0.149) + - + (0 \times 0) + (0 \times 0) + (0 \times 0.025) + (0 \times 0.149) + \\
& (0 \times 0.448) + -)\big)^{-1}
\end{aligned}$$

$$k = \left(1 - \begin{matrix} -+ & 0.001+ & 0.003+ & 0.010+ & 0+ \\ 0+ & -+ & 0.015+ & 0.044+ & 0+ \\ 0+ & 0.005+ & -+ & 0.096+ & 0+ \\ 0+ & 0+ & 0+ & -+ & 0+ \\ 0+ & 0+ & 0+ & 0+ & - \end{matrix} \right)^{-1}$$

k= 1.212

Before using equations (6.13-6.15) to find (β^m) and (M_{H_U}), we need to utilise equations (6.11-6.12) to find ($\beta^{m'}$), ($\bar{M}'_{H_U}$), and ($\tilde{M}'_{H_U}$):

$\bar{M}'_{H_U} = k\left(\bar{M}_{H_{12}}\bar{M}_{H_{WEx}}\right)$ = 1.212× 0.663× 0.378= 0.304

$\tilde{M}'_{H_U} = k\left(\tilde{M}_{H_{12}}\tilde{M}_{H_{WEx}} + \tilde{M}_{H_{12}}\bar{M}_{H_{WEx}} + \tilde{M}_{H_{WEx}}\bar{M}_{H_{12}}\right)$ =

1.212×[(0×0)+(0.663×0)+(0×0.378)] = 0

Accordingly, when $\beta^m = \frac{\beta^{m'}}{(1-\bar{H}_U)}, where\ (m =$ 1,2,3,4,5), then:

$\beta^m = \frac{\beta^{m'}}{(1-\bar{H}_U)}$ $, where\ (m =$ 1,2,3,4,5), then:

$\beta^{m'} = k\left(M_{12}^m M_3^m + M_{12}^m M_{H_{WEx}} + M_3^m M_{H_{12}}\right)$

$\beta^{1'} = k\left(M_{12}^1 M_3^1 + M_{12}^1 M_{H_{WEx}} + M_3^1 M_{H_{12}}\right)$ =

1.212×[(0.023×0)+(0.023×0.378)+(0.663×0)]= 0.011

$\beta^{2'} = k\left(M_{12}^2 M_3^2 + M_{12}^2 M_{H_{WEx}} + M_3^2 M_{H_{12}}\right)$ =

1.212×[(0.099×0.025)+(0.099×0.378)+(0.663×0.025)] = 0.068

$\beta^{3'} = k\left(M_{12}^3 M_3^3 + M_{12}^3 M_{H_{WEx}} + M_3^3 M_{H_{12}}\right)$ =

1.212×[(0.215×0.149)+(0.215×0.378)+(0.663×0.149)] = 0.258

$\beta^{4'} = k\left(M_{12}^4 M_3^4 + M_{12}^4 M_{H_{WEx}} + M_3^4 M_{H_{12}}\right)$ =

1.212×[(0×0.448)+(0×0.378)+(0.663×0.448)]= 0.360

$\beta^{5'} = k\left(M_{12}^5 M_3^5 + M_{12}^5 M_{H_{WEx}} + M_3^5 M_{H_{12}}\right)$ = 1. 212×[(0×0)+(0×0.378)+(0.663×0)]= 0

Accordingly, $\beta^1, \beta^2, \beta^3, \beta^4, and\ \beta^5$can be found using equation (6.14) as follows:

When, $m = 1,\ then\ \frac{\beta^{1'}}{1-\bar{H}_U'} = \frac{0.011}{1-0.304} = 0.015$

When, $m = 2,\ then\ \frac{\beta^{2'}}{1-\bar{H}_U'} = \frac{0.068}{1-0.304} = 0.098$

When, $m = 3,\ then\ \frac{\beta^{3'}}{1-\bar{H}_U'} = \frac{0.258}{1-0.304} = 0.370$

When, $m = 4,\ then\ \frac{\beta^{4'}}{1-\bar{H}_U'} = \frac{0.360}{1-0.304} = 0.517$

When, $m = 5,\ then\ \frac{\beta^{5'}}{1-\bar{H}_U'} = \frac{0}{1-0.304} = 0$

Furthermore, finding M_{H_U} can be done using equation (6.15) as follows:

$$M_{H_U} = \frac{\widetilde{M}_{H_U}'}{1-\bar{M}_{H_U}'} = \frac{0}{1-0.304} = 0$$

As a result, the aggregation of TP criterion for pilot 1 can be presented as follows (see Table 6.19):

$\widetilde{TP}_{Pilot1}$ ={(2% V. Good), (10% Good), (37% Average), (52% Low), (0% Basic)}

II.1.2 Non-Technical Skills (NTS)

The following is the aggregation process of pilot's 1 NTS, in relation to the sub-criteria of decision-making skills (DM), situation awareness skills (SA), communication skills (CS), and teamwork & Leadership skills (T&L), based on the information given by Pilot 1. Using ER equations can applied as follows:

Aggregating Pilot's 1 NTS Sub-Criteria $\widetilde{\mathrm{NTS}}_{\mathrm{DM}}$, $\widetilde{\mathrm{NTS}}_{\mathrm{SA}}$, $\widetilde{\mathrm{NTS}}_{\mathrm{CS}}$ and $\widetilde{\mathrm{NTS}}_{\mathrm{T\&L}}$ using ER algorithms, we need to define the following:

$\widetilde{\mathrm{NTS}}_{\mathrm{DM}}$, which represents the sub-criterion Decision Making skills (DM);

$\widetilde{\mathrm{NTS}}_{\mathrm{SA}}$, which represents the sub-criterion Situation Awareness skills (SA);

$\widetilde{\mathrm{NTS}}_{\mathrm{CS}}$, which represents the sub-criterion Communication Skills (CS); and

$\widetilde{\mathrm{NTS}}_{\mathrm{T\&L}}$, which represents the sub-criterion Teamwork & Leadership skills (T&L)

Based on the given fuzzy information of DM, SA, CS and T&L for Pilot 1, the results from the mapping process are as follows:

$R\widetilde{\mathrm{NTS}}_{\mathrm{DM}}$ = {(V. Good, 0.36), (Good, 0.64), (Average, 0), (Bad, 0), (V. Bad, 0)}

$R\widetilde{\mathrm{NTS}}_{\mathrm{SA}}$= {(V. Good, 0.14), (Good, 0.56), (Average, 0.27), (Bad, 0.03), (V. Bad, 0)}

$R\widetilde{\mathrm{NTS}}_{\mathrm{CS}}$= {(V. Good, 0.14), (Good, 0.56), (Average, 0.24), (Bad, 0.03), (V. Bad, 0)}

$R\widetilde{\mathrm{NTS}}_{\mathrm{T\&L}}$= {(V. Good, 0), (Good, 0), (Average, 0.72), (Bad, 0.24), (V. Bad, 0.04)}

The global weights obtained by ANP are as follows:

ω_{DM}= 0.045, ω_{SA}= 0.094, ω_{CS}= 0.142 and $\omega_{T\&L}$= 0.325

Where:

ω_{DM}, is the global weight assigned for NTS-DM;

ω_{SA}, is the global weight assigned for NTS-SA;

ω_{CS}, represents the global weight assigned for NTS-CS; and

$\omega_{T\&L}$, represents the global weight assigned for NTS-T&L.

Since the weights' sums are not equal to 1, they must be normalised. To normalise the weight for each criterion, divide the weight of each criterion to the sum of all criteria. The sum of DM, SA, CS and T&L are as follows:

$\omega_{DM} + \omega_{SA} + \omega_{CS} + \omega_{T\&L} =$ 0.045 + 0.094 + 0.142 + 0.325 = 0.606.

A normalised ω_{DM}= 0.045/0.606= 0.075.

Similarly, ω_{SA}= 0.155, ω_{CS}= 0.234 and $\omega_{T\&L}$= 0.536

The aggregation process of the first two criterion of NTS, $\widetilde{NTS}_{DM}$ and $\widetilde{NTS}_{SA}$, are as follows:

M_1^mrepresents the subset $\widetilde{NTS}_{DM}$, and M_2^m represent the subset $\widetilde{NTS}_{SA}$. Using ER equation (6.4), can obtain the followings:

$M_1^m = \omega_{DM}\beta_1^m$, where ($m$ = 1,2,3,4,5)

$M_2^m = \omega_{SA}\beta_2^m$,   where ($m$ = 1,2,3,4,5)

As a result, the following table has been constructed:

When, m= 1, M_1^1= 0.075×0.36 = 0.027, M_2^1= 0.155×0.14= 0.022
m= 2, M_1^2= 0.075×0.64 = 0.048, M_2^2= 0.155×0.56= 0.087
m= 3, M_1^3= 0.075×0= 0, M_2^3= 0.155×0.27= 0.042
m= 4, M_1^4= 0.075×0= 0, M_2^4= 0.155×0.03= 0.005
m= 5, M_1^5= 0.075×0= 0, M_2^5= 0.155×0= 0

When $M_{H_{DM}}$ represents the individual remaining belief for $\mathrm{M}_1^{\mathrm{m}}$, and $M_{H_{SA}}$ represents the individual remaining belief for $\mathrm{M}_2^{\mathrm{m}}$, therefore, equation 6.5, can be applied as follows:

- $M_{H_{DM}} = \bar{M}_{H_{DM}} + \widetilde{M}_{H_{DM}}$
- $M_{H_{SA}} = \bar{M}_{H_{SA}} + \widetilde{M}_{H_{SA}}$

$\bar{M}_{H_{DM}}, \widetilde{M}_{H_{DM}}$, and $\bar{M}_{H_{SA}}\widetilde{M}_{H_{SA}}$ can be found by applying equations (6.6-6.7), as follow:

- $\bar{M}_{H_{DM}} = 1 - \omega_{DM}$ =1- 0.075 = 0.926
- $\bar{M}_{H_{SA}} = 1 - \omega_{SA}$ =1- 0.155 = 0.845
- $\widetilde{M}_{H_{DM}} = \omega_{WDM}(1 - \sum_m^5 \beta_1^m)$ = 0.926× (1- (0.36+0.64+0+0+0)) = 0
- $\widetilde{M}_{H_{SA}} = \omega_{SA}(1 - \sum_m^5 \beta_2^m)$ = 0.845× (1- (0.14+0.56+0.27+0.03+0)) = 0
- $M_{H_{DM}} = \bar{M}_{H_{DM}} + \widetilde{M}_{H_{DM}}$ = 0.926+0= 0.926
- $M_{H_{SA}} = \bar{M}_{H_{SA}} + \widetilde{M}_{H_{SA}}$ = 0.845+0= 0.845

By using equations (6.8-6.11), to find $\beta^{m'} = k\left(M_1^m M_2^m + M_1^m M_{H_{SA}} + M_2^m M_{H_{DM}}\right)^{-1}$, ($\bar{M}'_{H_U}$), and ($\widetilde{M}'_{H_U}$), first we need to find k using equation (6.8):

$k = [1 - \sum_{T=1}^5 \sum_{R=1\neq T}^5 M_1^T M_2^R]^{-1}$

$$k=\left(1-\begin{matrix} -+ & M_1^1M_2^2+ & M_1^1M_2^3+ & M_1^1M_2^4+ & M_1^1M_2^5+\\ M_1^2M_2^1+ & -+ & M_1^2M_2^3+ & M_1^2M_2^4+ & M_1^2M_2^5+\\ M_1^3M_2^1+ & M_1^3M_2^2+ & -+ & M_1^3M_2^4+ & M_1^3M_2^5+\\ M_1^4M_2^1+ & M_1^4M_2^2+ & M_1^4M_2^3+ & -+ & M_1^4M_2^5+\\ M_1^5M_2^1+ & M_1^5M_2^2+ & M_1^5M_2^3+ & M_1^5M_2^4+ & - \end{matrix}\right)^{-1}$$

$$k=\quad \big(1-(-+(0.027\times 0.087)+(0.027\times 0.042)+(0.027\times 0.005)+(0.027\times 0)+(0.048\times 0.022)+-+(0.048\times 0.042)+(0.048\times 0.005)+(0.048\times 0)+(0\times 0.022)+(0\times 0.087)+-+(0\times 0.005)+(0\times 0)+(0\times 0.022)+(0\times 0.087)+(0\times 0.042)+-+(0\times 0)+(0\times 0.022)+(0\times 0.087)+(0\times 0.042)+(0\times 0.005)+-)\big)^{-1}$$

$$k=\left(1-\begin{matrix} -+ & 0.002+ & 0.001+ & 0+ & 0+\\ 0.001+ & -+ & 0.002+ & 0+ & 0+\\ 0+ & 0+ & -+ & 0+ & 0+\\ 0+ & 0+ & 0+ & -+ & 0+\\ 0+ & 0+ & 0+ & 0+ & - \end{matrix}\right)^{-1}$$

k= 1.007

Then, before using equations (6.12-6.13) to find (β^m) and (M_{H_U}), we need to utilise equations (6.8-6.11), to find ($\beta^{m'}$), ($\bar{M}'_{H_U}$), and ($\tilde{M}'_{H_U}$), as follow:

$\bar{M}'_{H_U}=K(\bar{M}_{H_{DM}}\bar{M}_{H_{SA}})$ = 1.007× 0.926× 0.845= 0.788

$\tilde{M}'_{H_U}=K(\tilde{M}_{H_{DM}}\tilde{M}_{H_{SA}}+\tilde{M}_{DM}\bar{M}_{H_{SA}}+\bar{M}_{H_{DM}}\tilde{M}_{H_{SA}})$ =

1.007×[(0×0)+(0.926×0)+(0×0.845)]=0

Accordingly, when $\beta^m=\frac{\beta^{m'}}{(1-\bar{H}_U)}$ $,where\ (m=1{,}2{,}3{,}4{,}5)$, then:

$\beta^{m'}=k\big(M_1^mM_2^m+M_1^mM_{H_{SA}}+M_2^mM_{H_{DM}}\big)$

$\beta^{1'}=k\big(M_1^1M_2^1+M_1^1M_{H_{SA}}+M_2^1M_{H_{DM}}\big)=$

1.007×[(0.027×0.022)+(0.027×0.845)+(0.926×0.022)]= 0.044

$\beta^{2'}=k\big(M_1^2M_2^2+M_1^2M_{H_{SA}}+M_2^2M_{H_{DM}}\big)=$

1.007×[(0.048×0.087)+(0.048×0.845)+(0.926×0.087)] = 0.126

$\beta^{3'} = k\left(M_1^3 M_2^3 + M_1^3 M_{H_{SA}} + M_2^3 M_{H_{DM}}\right)$ = 1.007×[(0×0.042)+(0×0.845)+(0.926×0.042)] = 0.039

$\beta^{4'} = k\left(M_1^4 M_2^4 + M_1^4 M_{H_{SA}} + M_2^4 M_{H_{DM}}\right) =$ 1.007×[(0×0.005)+(0×0.845)+(0.926×0.005)]= 0.004

$\beta^{5'} = k\left(M_1^5 M_2^5 + M_1^5 M_{H_{SA}} + M_2^5 M_{H_{DM}}\right)$ = 1.007×[(0×0)+(0×0.845)+(0.926×0)]= 0

From the above aggregations, the obtained results $\beta^{1'}$, $\beta^{2'}$,$\beta^{3'}$,$\beta^{4'}$, and $\beta^{5'}$represent $M_{12}^1, M_{12}^2, M_{12}^3, M_{12}^4$, and $M_{12}^5$for the first two aggregations. These will be used with the third aggregation similar to the above aggregation process. The following are the aggregation of the criterion CS with the aggregated result from DM and SA:

M_{12}^m represents the aggregated subset of $\widetilde{NTS}_{DM}$, and $\widetilde{NTS}_{SA}$, while M_3^m represents the subset $\widetilde{NTS}_{CS}$. Using the ER equation (6.6) can obtain the following:

$M_3^m = \omega_{CS}\beta_3^m$, where ($m$ = 1,2,3,4,5)

When, m= 1, M_{12}^1= 0.044, M_3^1= 0.234×0.14= 0.033

m= 2, M_{12}^2= 0.126, M_3^2= 0.234×0.56= 0.131

m= 3, M_{12}^3= 0.039, M_3^3= 0.234×0.27= 0.063

m= 4, M_{12}^4= 0.004, M_3^4= 0.234×0.03= 0.007

m= 5, M_{12}^5= 0, M_3^5= 0.234×0= 0

When $M_{H_{12}}$ represents the individual remaining belief for $\mathrm{M}_{12}^{\mathrm{m}}$, and $M_{H_{CS}}$ represents the individual remaining belief for $\mathrm{M}_3^{\mathrm{m}}$, equation 6.7 can be applied as follows:

- $M_{H_{CS}} = \bar{M}_{H_{CS}} + \widetilde{M}_{H_{CS}}$

$\bar{M}_{H_{CS}}$, $\widetilde{M}_{H_{CS}}$ can be found by applying equations (6.8-6.9) as follows:

- $\bar{M}_{H_{CS}} = 1 - \omega_{CS}$ = 1- 0.234= 0.766
- $\widetilde{M}_{H_{CS}} = \omega_{CS}(1 - \sum_m^5 \beta_3^m)$ = 0.766× (1- (0.14+0.56+0.27+0.03+0))= 0
- $M_{H_{CS}} = \bar{M}_{H_{CS}} + \widetilde{M}_{H_{CS}}$ = 0.766+0= 0.766

By using equations (6.10-6.13) to find $\beta^{m'} = k\left(M_{12}^{m}M_{3}^{m} + M_{12}^{m}M_{H_{CS}} + M_{3}^{m}M_{H_{12}}\right)^{-1}$, $(\bar{M}'_{H_U})$, and $(\widetilde{M}'_{H_U})$, we find k using equation (6.13):

$k = [1 - \sum_{T=1}^{5}\sum_{R=1\neq T}^{5} M_{12}^{T}M_{3}^{R}]^{-1}$

$$k = \left(\begin{array}{cccccc} & -+ & M_{12}^{1}M_{3}^{2} + & M_{12}^{1}M_{3}^{3} + & M_{12}^{1}M_{3}^{4} + & M_{12}^{1}M_{3}^{5} + \\ & M_{12}^{2}M_{3}^{1} + & -+ & M_{12}^{2}M_{3}^{3} + & M_{12}^{2}M_{3}^{4} + & M_{12}^{2}M_{3}^{5} + \\ 1 - & M_{12}^{3}M_{3}^{1} + & M_{12}^{3}M_{3}^{2} + & -+ & M_{12}^{3}M_{3}^{4} + & M_{12}^{3}M_{3}^{5} + \\ & M_{12}^{4}M_{3}^{1} + & M_{12}^{4}M_{3}^{2} + & M_{12}^{4}M_{3}^{3} + & -+ & M_{12}^{4}M_{3}^{5} + \\ & M_{12}^{5}M_{3}^{1} + & M_{12}^{5}M_{3}^{2} + & M_{12}^{5}M_{3}^{3} + & M_{12}^{5}M_{3}^{4} + & - \end{array}\right)^{-1}$$

$k = \left(1 - (- + (0.044 \times 0.131) + (0.044 \times 0.063) + (0.044 \times 0.077) + (0.044 \times 0) + (0.126 \times 0.033) + - + (0.126 \times 0.063) + (0.126 \times 0.007) + (0.126 \times 0) + (0.039 \times 0.033) + (0.039 \times 0.131) + - + (0.039 \times 0.007) + (0.039 \times 0) + (0.004 \times 0.033) + (0.004 \times 0.131) + (0.004 \times 0.063) + - + (0.004 \times 0) + (0 \times 0.033) + (0 \times 0.131) + (0 \times 0.063) + (0 \times 0.007) + -)\right)^{-1}$

$$k = \left(\begin{array}{cccccc} & -+ & 0.006 + & 0.003 + & 0 + & 0 + \\ & 0.004 + & -+ & 0.008 + & 0.001 + & 0 + \\ 1 - & 0.001 + & 0.005 + & -+ & 0 + & 0 + \\ & 0 + & 0.001 + & 0 + & -+ & 0 + \\ & 0 + & 0 + & 0 + & 0 + & - \end{array}\right)^{-1}$$

$k = 1.03$

Before using equations (6.13-6.15) to find (β^{m}) and (M_{H_U}), we need to utilise equations (6.11-6.12) to find $(\beta^{m'})$, $(\bar{M}'_{H_U})$, and $(\widetilde{M}'_{H_U})$:

$\bar{M}'_{H_U} = k\left(\bar{M}_{H_{12}}\bar{M}_{H_{CS}}\right) = 1.03 \times 0.788 \times 0.766 = 0.621$

$\widetilde{M}'_{H_U} = k\left(\widetilde{M}_{H_{12}}\widetilde{M}_{H_{CS}} + \widetilde{M}_{H_{12}}\bar{M}_{H_{CS}} + \widetilde{M}_{H_{CS}}\bar{M}_{H_{12}}\right) = 1.03 \times [(0\times0)+(0.788\times0)+(0\times0.766)] = 0$

Accordingly, when $\beta^{m} = \frac{\beta^{m'}}{(1-\bar{H}_U)}, where\ (m = 1,2,3,4,5)$, then:

$\beta^{m} = \frac{\beta^{m'}}{(1-\bar{H}_U)}\ , where\ (m = 1,2,3,4,5)$, then:

$\beta^{m'} = k\left(M_{12}^{m}M_{3}^{m} + M_{12}^{m}M_{H_{CS}} + M_{3}^{m}M_{H_{12}}\right)$

$\beta^{1'} = k\left(M_{12}^{1}M_{3}^{1} + M_{12}^{1}M_{H_{CS}} + M_{3}^{1}M_{H_{12}}\right)$ =

1.03×[(0.044×0.033)+(0.044×0.766)+(0.788×0.033)]= 0.062

$\beta^{2'} = k\left(M_{12}^{2}M_{3}^{2} + M_{12}^{2}M_{H_{CS}} + M_{3}^{2}M_{H_{12}}\right)$ =

1.03×[(0.126×0.131)+(0.126×0.766)+(0.788×0.131)] = 0.222

$\beta^{3'} = k\left(M_{12}^{3}M_{3}^{3} + M_{12}^{3}M_{H_{CS}} + M_{3}^{3}M_{H_{12}}\right)$ =

1.03×[(0.039×0.063)+(0.039×0.766)+(0.788×0.063)] = 0.085

$\beta^{4'} = k\left(M_{12}^{4}M_{3}^{4} + M_{12}^{4}M_{H_{CS}} + M_{3}^{4}M_{H_{12}}\right)$ =

1.03×[(0.004×0.007)+(0.004×0.766)+(0.788×0)]= 0.009

$\beta^{5'} = k\left(M_{12}^{5}M_{3}^{5} + M_{12}^{5}M_{H_{CS}} + M_{3}^{5}M_{H_{12}}\right)$ = 1.03× [(0×0)+(0×0.766)+(0.788×0)]= 0

From the above aggregations, the obtained results $\beta^{1'}$, $\beta^{2'}$, $\beta^{3'}$, $\beta^{4'}$, and $\beta^{5'}$ represent M_{123}^{1}, M_{123}^{2}, M_{123}^{3}, M_{123}^{4}, and M_{123}^{5} for the first three aggregations. These will be used with the fourth aggregation similar to the above aggregation process. The following are the aggregation of the criterion T&L with the aggregated result from DM, SA and CS:

M_{123}^{m} represents the aggregated subset of $\widetilde{NTS}_{DM}$, $\widetilde{NTS}_{SA}$ and $\widetilde{NTS}_{CS}$, while M_{4}^{m} represents the subset $\widetilde{NTS}_{T\&L}$. Using the ER equation (6.6) can obtain the following:

$M_{4}^{m} = \omega_{T\&L}\beta_{4}^{m}$, where ($m$ = 1,2,3,4,5)

When, m= 1, M_{123}^{1}= 0.062, M_{4}^{1}= 0.536×0= 0

m= 2, M_{123}^{2}= 0.222, M_{4}^{2}= 0.536×0= 0

m= 3, M_{123}^{3}= 0.085, M_{4}^{3}= 0.536×0.72= 0.386

m= 4, M_{123}^{4}= 0.009, M_{4}^{4}= 0.536×0.24= 0.129

m= 5, M_{123}^{5}= 0, M_{4}^{5}= 0.536×0.04= 0.021

When $M_{H_{123}}$ represents the individual remaining belief for $\mathrm{M}_{123}^{\mathrm{m}}$, and $M_{H_{T\&L}}$ represents the individual remaining belief for $\mathrm{M}_{4}^{\mathrm{m}}$, equation 6.7 can be applied as follows:

- $M_{H_{T\&L}} = \bar{M}_{H_{T\&L}} + \widetilde{M}_{H_{T\&L}}$

$\overline{M}_{H_{T\&L}}, \widetilde{M}_{H_{T\&L}}$ can be found by applying equations (6.8-6.9) as follows:

- $\overline{M}_{H_{T\&L}} = 1 - \omega_{T\&L}$ = 1- 0.536= 0.464
- $\widetilde{M}_{H_{T\&L}} = \omega_{T\&L}(1 - \sum_{m}^{5} \beta_4^m)$ = 0.464× (1- (0+0+0.72+0.24+0.04))= 0
- $M_{H_{T\&L}} = \overline{M}_{H_{T\&L}} + \widetilde{M}_{H_{T\&L}}$ = 0.464+0= 0.464

By using equations (6.10-6.13) to find $\beta^{m'} = k\big(M_{123}^m M_4^m + M_{123}^m M_{H_{T\&L}} + M_4^m M_{H_{123}}\big)^{-1}$, $(\overline{M}'_{H_U})$, and $(\widetilde{M}'_{H_U})$, we find k using equation (6.13):

$$k = [1 - \textstyle\sum_{T=1}^{5} \sum_{R=1 \neq T}^{5} M_{123}^T M_4^R]^{-1}$$

$$k = \left(\begin{array}{cccccc} & - + & M_{123}^1 M_4^2 + & M_{123}^1 M_4^3 + & M_{123}^1 M_4^4 + & M_{123}^1 M_4^5 + \\ & M_{123}^2 M_4^1 + & - + & M_{123}^2 M_4^3 + & M_{123}^2 M_4^4 + & M_{123}^2 M_4^5 + \\ 1 - & M_{123}^3 M_4^1 + & M_{123}^3 M_4^2 + & - + & M_{123}^3 M_4^4 + & M_{123}^3 M_4^5 + \\ & M_{123}^4 M_4^1 + & M_{123}^4 M_4^2 + & M_{123}^4 M_4^3 + & - + & M_{123}^4 M_4^5 + \\ & M_{123}^5 M_4^1 + & M_{123}^5 M_4^2 + & M_{123}^5 M_4^3 + & M_{123}^5 M_4^4 + & - \end{array} \right)^{-1}$$

$$k = \big(1 - (- + (0.062 \times 0) + (0.062 \times 0.386) + (0.062 \times 0.129) + (0.062 \times 0.021) + (0.222 \times 0) + - + (0.222 \times 0.386) + (0.222 \times 0.129) + (0.222 \times 0.021) + (0.085 \times 0) + (0.085 \times 0) + - + (0.085 \times 0.129) + (0.085 \times 0.021) + (0.009 \times 0) + (0.009 \times 0) + (0.009 \times 0.386) + - + (0.009 \times 0.021) + (0 \times 0) + (0 \times 0) + (0 \times 0.386) + (0 \times 0.129) + -)\big)^{-1}$$

$$k = \left(\begin{array}{cccccc} & - + & 0 + & 0.024 + & 0.008 + & 0.001 + \\ & 0 + & - + & 0.086 + & 0.029 + & 0.005 + \\ 1 - & 0 + & 0 + & - + & 0.011 + & 0.002 + \\ & 0 + & 0 + & 0.004 + & - + & 0 + \\ & 0 + & 0 + & 0 + & 0 + & - \end{array} \right)^{-1}$$

k= 1.204

Before using equations (6.13-6.15) to find (β^m) and (M_{H_U}), we need to utilise equations (6.11-6.12) to find $(\beta^{m'})$, $(\overline{M}'_{H_U})$, and $(\widetilde{M}'_{H_U})$:

$\overline{M}'_{H_U} = k\big(\overline{M}_{H_{123}} \overline{M}_{H_{T\&L}}\big)$ = 1.204× 0.621× 0.464= 0.347

$\widetilde{M}'_{H_U} = k\left(\widetilde{M}_{H_{123}}\widetilde{M}_{H_{T\&L}} + \widetilde{M}_{H_{123}}\overline{M}_{H_{T\&L}} + \widetilde{M}_{H_{T\&L}}\overline{M}_{H_{123}}\right)$ =

1.204×[(0×0)+(0.621×0)+(0×0.464)] = 0

Accordingly, when $\beta^m = \frac{\beta^{m'}}{(1-\overline{H}_U)}, where\ (m =$ 1,2,3,4,5), then:

$\beta^m = \frac{\beta^{m'}}{(1-\overline{H}_U)}$ $, where\ (m =$ 1,2,3,4,5), then:

$\beta^{m'} = k\left(M_{123}^m M_4^m + M_{123}^m M_{H_{T\&L}} + M_4^m M_{H_{123}}\right)$

$\beta^{1'} = k\left(M_{123}^1 M_4^1 + M_{123}^1 M_{H_{T\&L}} + M_4^1 M_{H_{123}}\right)$ =

1.204×[(0.062×0)+(0.062×0.464)+(0.621×0)]= 0.035

$\beta^{2'} = k\left(M_{123}^2 M_4^2 + M_{123}^2 M_{H_{T\&L}} + M_4^2 M_{H_{123}}\right)$ =

1.204×[(0.222×0)+(0.222×0.464)+(0.621×0)] = 0.124

$\beta^{3'} = k\left(M_{123}^3 M_4^3 + M_{123}^3 M_{H_{T\&L}} + M_4^3 M_{H_{123}}\right)$ =

1.204×[(0.085×0.386)+(0.085×0.464)+(0.621×0.386)] = 0.375

$\beta^{4'} = k\left(M_{123}^4 M_4^4 + M_{123}^4 M_{H_{T\&L}} + M_4^4 M_{H_{123}}\right)$ =

1.204×[(0.009×0.129)+(0.009×0.464)+(0.621×0.129)]= 0.103

$\beta^{5'} = k\left(M_{123}^5 M_4^5 + M_{123}^5 M_{H_{T\&L}} + M_4^5 M_{H_{123}}\right)$ =

1.204×[(0×0.021)+(0×0.464)+(0.621×0.021)]= 0.016

Accordingly, $\beta^1, \beta^2, \beta^3, \beta^4, and\ \beta^5$can be found using equation (6.14) as follows:

When, $m = 1,\ then\ \frac{\beta^{1'}}{1-\overline{H}'_U} = \frac{0.035}{1-0.347} = 0.053$

When, $m = 2,\ then\ \frac{\beta^{2'}}{1-\overline{H}'_U} = \frac{0.124}{1-0.347} = 0.190$

When, $m = 3,\ then\ \frac{\beta^{3'}}{1-\overline{H}'_U} = \frac{0.375}{1-0.347} = 0.575$

When, $m = 4,\ then\ \frac{\beta^{4'}}{1-\overline{H}'_U} = \frac{0.103}{1-0.347} = 0.157$

When, $m = 5,\ then\ \frac{\beta^{5'}}{1-\bar{H}'_U} = \frac{0.016}{1-0.347} = 0.025$

Furthermore, finding M_{H_U} can be done using equation (6.15) as follows:

$$M_{H_U} = \frac{\tilde{M}'_{H_U}}{1-\bar{M}'_{H_U}} = \frac{0}{1-0.347} = 0$$

As a result, the aggregation of NTS criterion for pilot 1 can be presented as follows (see Table 6.19):

$\widetilde{NTS}_{Pilot1}$ ={(5% V. Good), (19% Good), (57% Moderate), (16% Bad), (2% V. Bad)}

II.1.3 Fitness and Strength (F&S)

The following is the aggregation process of pilot's 1 F&S, in relation to the sub-criteria of operator age (OA), health issue (HI), and body strength (BS), based on the information given by Pilot 1. Using ER equations can applied as follows:

Aggregating Pilot's 1 F&S Sub-Criteria $\widetilde{\text{F\&S}}_{\text{OA}}$, $\widetilde{\text{F\&S}}_{\text{HI}}$, and $\widetilde{\text{F\&S}}_{\text{BS}}$ using ER algorithms, we need to define the following:

$\widetilde{\text{F\&S}}_{\text{OA}}$, which represents the sub-criterion Operator Age (OA);

$\widetilde{\text{F\&S}}_{\text{HI}}$, which represents the sub-criterion Health Issue (HI);

$\widetilde{\text{F\&S}}_{\text{BS}}$, which represents the sub-criterion Body Strength (BS).

Based on the given fuzzy information of OA, HI, and BS for Pilot 1, the results from the mapping process are as follows:

$F\&S - OA_{p1}$ = {(Fit, 0.06), (Good, 0.24), (Moderate, 0.63), (Bad, 0.07), (Unfit, 0)}

$F\&S - HI_{p1}$= {(Fit, 0.80), (Good, 0.18), (Moderate, 0.02), (Bad, 0), (Unfit, 0)}

$F\&S - BS_{p1}$= {(Fit, 0.80), (Good, 0.18), (Moderate, 0.02), (Bad, 0), (Unfit, 0)}

The global weights obtained by ANP are as follows:

ω_{OA}= 0.008, ω_{HI}= 0.091, and ω_{BS}= 0.064

Where:

ω_{OA}, is the global weight assigned for F&S-OA;

ω_{HI}, is the global weight assigned for F&S-HI;

ω_{BS}, represents the global weight assigned for F&S-BS.

Since the weights' sums are not equal to 1, they must be normalised. To normalise the weight for each criterion, divide the weight of each criterion to the sum of all criteria. The sum of OA, HI, and BS are as follows:

$\omega_{OA} + \omega_{HI} + \omega_{BS} =$ 0.008+ 0.091+ 0.064= 0.163.

A normalised ω_{OA}= 0.008/0.163= 0.049.

Similarly, ω_{HI}= 0.558 and ω_{BS}= 0.393

The aggregation process of the first two criterion of F&S, $\widetilde{F\&S}_{OA}$ and $\widetilde{F\&S}_{HI}$, are as follows: M_1^mrepresents the subset $\widetilde{F\&S}_{OA}$, and M_2^m represent the subset $\widetilde{F\&S}_{HI}$. Using ER equation (6.4), can obtain the followings:

$M_1^m = \omega_{OA}\beta_1^m$, where ($m$ = 1,2,3,4,5)

$M_2^m = \omega_{HI}\beta_2^m$, where ($m$ = 1,2,3,4,5)

As a result, the following table has been constructed:

When, m= 1, M_1^1= 0.049×0.06= 0.003, M_2^1= 0.558×0.8= 0.447

m= 2, M_1^2= 0.049×0.24 = 0.012, M_2^2= 0.558×0.18= 0.100

m= 3, M_1^3= 0.049×0.63= 0.031, M_2^3= 0.558×0.02= 0.011

m= 4, M_1^4= 0.049×0.07= 0.003, M_2^4= 0.558×0= 0

m= 5, M_1^5= 0.049×0= 0, M_2^5= 0.558×0= 0

When $M_{H_{OA}}$ represents the individual remaining belief for $\mathrm{M}_1^{\mathrm{m}}$, and $M_{H_{HI}}$ represents the individual remaining belief for $\mathrm{M}_2^{\mathrm{m}}$, therefore, equation 6.5, can be applied as follows:

- $M_{H_{OA}} = \bar{M}_{H_{OA}} + \widetilde{M}_{H_{OA}}$
- $M_{H_{HI}} = \bar{M}_{H_{HI}} + \widetilde{M}_{H_{HI}}$

$\overline{M}_{H_{OA}}, \widetilde{M}_{H_{OA}}$, and $\overline{M}_{H_{HI}}\widetilde{M}_{H_{HI}}$ can be found by applying equations (6.6-6.7), as follow:

- $\overline{M}_{H_{OA}} = 1 - \omega_{OA}$ =1- 0.049 = 0.951
- $\overline{M}_{H_{HI}} = 1 - \omega_{HI}$ =1- 0.558= 0.442
- $\widetilde{M}_{H_{OA}} = \omega_{WOA}(1 - \sum_{m}^{5} \beta_1^m)$ = 0.951× (1- (0.06+0.24+0.63+0.07+0)) = 0
- $\widetilde{M}_{H_{HI}} = \omega_{HI}(1 - \sum_{m}^{5} \beta_2^m)$ = 0.442× (1- (0.8+0.18+0.02+0+0)) = 0
- $M_{H_{OA}} = \overline{M}_{H_{OA}} + \widetilde{M}_{H_{OA}}$ = 0.951+0= 0.951
- $M_{H_{HI}} = \overline{M}_{H_{HI}} + \widetilde{M}_{H_{HI}}$ = 0.442+0= 0.442

By using equations (6.8-6.11), to find $\beta^{m'} = k\left(M_1^m M_2^m + M_1^m M_{H_{HI}} + M_2^m M_{H_{OA}}\right)^{-1}$, $(\overline{M}'_{H_U})$, and $(\widetilde{M}'_{H_U})$, first we need to find k using equation (6.8):

$k = [1 - \sum_{T=1}^{5} \sum_{R=1 \neq T}^{5} M_1^T M_2^R]^{-1}$

$$k = \left(\begin{array}{cccccc} & - + & M_1^1 M_2^2 + & M_1^1 M_2^3 + & M_1^1 M_2^4 + & M_1^1 M_2^5 + \\ & M_1^2 M_2^1 + & - + & M_1^2 M_2^3 + & M_1^2 M_2^4 + & M_1^2 M_2^5 + \\ 1 - & M_1^3 M_2^1 + & M_1^3 M_2^2 + & - + & M_1^3 M_2^4 + & M_1^3 M_2^5 + \\ & M_1^4 M_2^1 + & M_1^4 M_2^2 + & M_1^4 M_2^3 + & - + & M_1^4 M_2^5 + \\ & M_1^5 M_2^1 + & M_1^5 M_2^2 + & M_1^5 M_2^3 + & M_1^5 M_2^4 + & - \end{array}\right)^{-1}$$

$$k = \big(1 - (- + (0.003 \times 0.100) + (0.003 \times 0.011) + (0.003 \times 0) + (0.003 \times 0) + (0.012 \times 0.447) + - + (0.012 \times 0.011) + (0.012 \times 0) + (0.012 \times 0) + (0.031 \times 0.447) + (0.031 \times 0.100) + - + (0.031 \times 0) + (0.031 \times 0) + (0.003 \times 0.447) + (0.003 \times 0.100) + (0.003 \times 0.011) + - + (0.003 \times 0) + (0 \times 0.447) + (0 \times 0.100) + (0 \times 0.011) + (0 \times 0) + -)\big)^{-1}$$

$$k = \left(\begin{array}{cccccc} & - + & 0 + & 0 + & 0 + & 0 + \\ & 0.005 + & - + & 0 + & 0 + & 0 + \\ 1 - & 0.014 + & 0.003 + & - + & 0 + & 0 + \\ & 0.002 + & 0 + & 0 + & - + & 0 + \\ & 0 + & 0 + & 0 + & 0 + & - \end{array}\right)^{-1}$$

k= 1.025

Then, before using equations (6.12-6.13) to find (β^{m}) and (M_{H_U}), we need to utilise equations (6.8-6.11), to find ($\beta^{m\prime}$), ($\bar{M}'_{H_U}$), and ($\widetilde{M}'_{H_U}$), as follow:

$\bar{M}'_{H_U} = K(\bar{M}_{H_{OA}}\bar{M}_{H_{HI}})$ = 1.025× 0.951× 0.442= 0.431

$\widetilde{M}'_{H_U} = K(\widetilde{M}_{H_{OA}}\widetilde{M}_{H_{HI}} + \widetilde{M}_{OA}\bar{M}_{H_{HI}} + \bar{M}_{H_{OA}}\widetilde{M}_{H_{HI}})$ =

1.025×[(0×0)+(0.951×0)+(0×0.442)]=0

Accordingly, when $\beta^{m} = \frac{\beta^{m\prime}}{(1-\bar{H}_U)}$ $, where\ (m = 1,2,3,4,5)$, then:

$\beta^{m\prime} = k\left(M_1^m M_2^m + M_1^m M_{H_{HI}} + M_2^m M_{H_{OA}}\right)$

$\beta^{1\prime} = k\left(M_1^1 M_2^1 + M_1^1 M_{H_{HI}} + M_2^1 M_{H_{OA}}\right) =$

1.025×[(0.003×0.447)+(0.003×0.442)+(0.951×0.447)]= 0.438

$\beta^{2\prime} = k\left(M_1^2 M_2^2 + M_1^2 M_{H_{HI}} + M_2^2 M_{H_{OA}}\right) =$

1.025×[(0.012×0.100)+(0.012×0.442)+(0.951×0.100)] = 0.105

$\beta^{3\prime} = k\left(M_1^3 M_2^3 + M_1^3 M_{H_{HI}} + M_2^3 M_{H_{OA}}\right) =$

1.025×[(0.031×0.011)+(0.031×0.442)+(0.951×0.011)] = 0.025

$\beta^{4\prime} = k\left(M_1^4 M_2^4 + M_1^4 M_{H_{HI}} + M_2^4 M_{H_{OA}}\right) =$

1.025×[(0.003×0)+(0.003×0.442)+(0.951×0)]= 0.002

$\beta^{5\prime} = k\left(M_1^5 M_2^5 + M_1^5 M_{H_{HI}} + M_2^5 M_{H_{OA}}\right) =$ 1.025×[(0×0)+(0×0.442)+(0.951×0)]= 0

From the above aggregations, the obtained results $\beta^{1\prime}$, $\beta^{2\prime}$,$\beta^{3\prime}$,$\beta^{4\prime}$, and $\beta^{5\prime}$represent $M_{12}^1, M_{12}^2, M_{12}^3, M_{12}^4$, and $M_{12}^5$for the first two aggregations. These will be used with the third aggregation similar to the above aggregation process. The following are the aggregation of the criterion BS with the aggregated result from OA and HI:

M_{12}^m represents the aggregated subset of $\widetilde{F\&S}_{OA}$, and $\widetilde{F\&S}_{HI}$, while M_3^m represents the subset $\widetilde{F\&S}_{BS}$. Using the ER equation (6.6) can obtain the following:

$M_3^m = \omega_{BS}\beta_3^m$, where ($m$ = 1,2,3,4,5)

When, m= 1, M_{12}^{1}= 0.438, M_{3}^{1}= 0.393×0.8= 0.314

m= 2, M_{12}^{2}= 0.105, M_{3}^{2}= 0.393×0.18= 0.071

m= 3, M_{12}^{3}= 0.025, M_{3}^{3}= 0.393×0.02= 0.008

m= 4, M_{12}^{4}= 0.002, M_{3}^{4}= 0.393×0= 0

m= 5, M_{12}^{5}= 0, M_{3}^{5}= 0.393×0= 0

When $M_{H_{12}}$ represents the individual remaining belief for $\mathrm{M}_{12}^{\mathrm{m}}$, and $M_{H_{BS}}$ represents the individual remaining belief for $\mathrm{M}_{3}^{\mathrm{m}}$, equation 6.7 can be applied as follows:

- $M_{H_{BS}} = \overline{M}_{H_{BS}} + \widetilde{M}_{H_{BS}}$

$\overline{M}_{H_{BS}}, \widetilde{M}_{H_{BS}}$ can be found by applying equations (6.8-6.9) as follows:

- $\overline{M}_{H_{BS}} = 1 - \omega_{BS}$ = 1- 0.393= 0.607
- $\widetilde{M}_{H_{BS}} = \omega_{BS}(1 - \sum_{m}^{5} \beta_3^m)$ = 0.607× (1- (0.8+0.18+0.02+0+0))= 0
- $M_{H_{BS}} = \overline{M}_{H_{BS}} + \widetilde{M}_{H_{BS}}$ = 0.607+0= 0.607

By using equations (6.10-6.13) to find $\beta^{m'} = k\left(M_{12}^{m}M_{3}^{m} + M_{12}^{m}M_{H_{BS}} + M_{3}^{m}M_{H_{12}}\right)^{-1}$, ($\overline{M}'_{H_U}$), and ($\widetilde{M}'_{H_U}$), we find k using equation (6.13):

$$k = [1 - \textstyle\sum_{T=1}^{5}\sum_{R=1 \neq T}^{5} M_{12}^{T}M_{3}^{R}]^{-1}$$

$$k = \left(1 - \begin{matrix} -+ & M_{12}^{1}M_{3}^{2} + & M_{12}^{1}M_{3}^{3} + & M_{12}^{1}M_{3}^{4} + & M_{12}^{1}M_{3}^{5} + \\ M_{12}^{2}M_{3}^{1} + & -+ & M_{12}^{2}M_{3}^{3} + & M_{12}^{2}M_{3}^{4} + & M_{12}^{2}M_{3}^{5} + \\ M_{12}^{3}M_{3}^{1} + & M_{12}^{3}M_{3}^{2} + & -+ & M_{12}^{3}M_{3}^{4} + & M_{12}^{3}M_{3}^{5} + \\ M_{12}^{4}M_{3}^{1} + & M_{12}^{4}M_{3}^{2} + & M_{12}^{4}M_{3}^{3} + & -+ & M_{12}^{4}M_{3}^{5} + \\ M_{12}^{5}M_{3}^{1} + & M_{12}^{5}M_{3}^{2} + & M_{12}^{5}M_{3}^{3} + & M_{12}^{5}M_{3}^{4} + & - \end{matrix} \right)^{-1}$$

$$k = \big(1 - (- + (0.438 \times 0.071) + (0.438 \times 0.008) + (0.438 \times 0) + (0.438 \times 0) + (0.105 \times 0.314) + - + (0.105 \times 0.008) + (0.105 \times 0) + (0.105 \times 0) + (0.025 \times 0.314) + (0.025 \times 0.071) + - + (0.025 \times 0) + (0.025 \times 0) + (0.002 \times 0.314) + (0.002 \times 0.071) + (0.002 \times 0.008) + - + (0.002 \times 0) + (0 \times 0.314) + (0 \times 0.071) + (0 \times 0.008) + (0 \times 0) + -)\big)^{-1}$$

$$k = \left(1 - \begin{matrix} -+ & 0.031+ & 0.003+ & 0+ & 0+ \\ 0.033+ & -+ & 0.001+ & 0+ & 0+ \\ 0.008+ & 0.002+ & -+ & 0+ & 0+ \\ 0+ & 0+ & 0+ & -+ & 0+ \\ 0+ & 0+ & 0+ & 0+ & - \end{matrix} \right)^{-1}$$

k= 1.085

Before using equations (6.13-6.15) to find (β^m) and (M_{H_U}), we need to utilise equations (6.11-6.12) to find ($\beta^{m\prime}$), ($\bar{M}'_{H_U}$), and ($\widetilde{M}'_{H_U}$):

$\bar{M}'_{H_U} = k\left(\bar{M}_{H_{12}}\bar{M}_{H_{BS}}\right)$ = 1.085× 0.663× 0.378= 0.304

$\widetilde{M}'_{H_U} = k\left(\widetilde{M}_{H_{12}}\widetilde{M}_{H_{BS}} + \widetilde{M}_{H_{12}}\bar{M}_{H_{BS}} + \widetilde{M}_{H_{BS}}\bar{M}_{H_{12}}\right)$ = 1.085×[(0×0)+(0.431×0)+(0×0.607)] = 0

Accordingly, when $\beta^m = \frac{\beta^{m\prime}}{(1-\bar{H}_U)}, where\ (m = 1,2,3,4,5)$, then:

$\beta^m = \frac{\beta^{m\prime}}{(1-\bar{H}_U)}\ , where\ (m = 1,2,3,4,5)$, then:

$\beta^{m\prime} = k\left(M_{12}^m M_3^m + M_{12}^m M_{H_{BS}} + M_3^m M_{H_{12}}\right)$

$\beta^{1\prime} = k\left(M_{12}^1 M_3^1 + M_{12}^1 M_{H_{BS}} + M_3^1 M_{H_{12}}\right)$ =

1.085×[(0.438×0.314)+(0.438×0.607)+(0.431×0.314)]= 0.585

$\beta^{2\prime} = k\left(M_{12}^2 M_3^2 + M_{12}^2 M_{H_{BS}} + M_3^2 M_{H_{12}}\right)$ =

1.085×[(0.105×0.071)+(0.105×0.607)+(0.431×0.071)] = 0.110

$\beta^{3\prime} = k\left(M_{12}^3 M_3^3 + M_{12}^3 M_{H_{BS}} + M_3^3 M_{H_{12}}\right)$ =

1.085×[(0.025×0.008)+(0.025×0.607)+(0.431×0.008)] = 0.021

$\beta^{4\prime} = k\left(M_{12}^4 M_3^4 + M_{12}^4 M_{H_{BS}} + M_3^4 M_{H_{12}}\right)$ =

1.085×[(0.002×0)+(0.002×0.607)+(0.431×0)]= 0.001

$\beta^{5\prime} = k\left(M_{12}^5 M_3^5 + M_{12}^5 M_{H_{BS}} + M_3^5 M_{H_{12}}\right)$ = 1.085× [(0×0)+(0×0.607)+(0.431×0)]= 0

Accordingly, $\beta^1, \beta^2, \beta^3, \beta^4, and\ \beta^5$can be found using equation (6.14) as follows:

When, $m = 1, \ then \ \frac{\beta^{1'}}{1-\bar{H}'_U} = \frac{0.585}{1-0.284} = 0.816$

When, $m = 2, \ then \ \frac{\beta^{2'}}{1-\bar{H}'_U} = \frac{0.110}{1-0.284} = 0.153$

When, $m = 3, \ then \ \frac{\beta^{3'}}{1-\bar{H}'_U} = \frac{0.021}{1-0.284} = 0.029$

When, $m = 4, \ then \ \frac{\beta^{4'}}{1-\bar{H}'_U} = \frac{0.001}{1-0.284} = 0.001$

When, $m = 5, \ then \ \frac{\beta^{5'}}{1-\bar{H}'_U} = \frac{0}{1-0.284} = 0$

Furthermore, finding M_{H_U} can be done using equation (6.15) as follows:

$$M_{H_U} = \frac{\tilde{M}'_{H_U}}{1- \bar{M}'_{H_U}} = \frac{0}{1-0.284} = 0$$

As a result, the aggregation of TP criterion for pilot 1 can be presented as follows (see Table 6.19):

$\widetilde{F\&S}_{P1}$ ={(82% Fit), (15% Good), (3% Moderate), (0% Bad), (0% Unfit)}

II.1.4 Aggregating main criteria

The following is the aggregation process of pilot’s 1 sub-criteria towards the main goal following the application of mapping process from the sub-criteria towards the main goal, in relation to the sub-criteria of technical proficiency (TP) personal fatigue (PF), non-technical skills (NTS), and fitness &strength (F&S), based on the aggregated result in previous section. Using ER equations can applied as follows:

Aggregating Pilot’s 1 overall goal Sub-Criteria $\widetilde{\mathrm{TP}}_{\mathrm{p1}}$, $\widetilde{\mathrm{PF}}_{\mathrm{p1}}$, $\widetilde{\mathrm{NTS}}_{\mathrm{p1}}$ and $\widetilde{\mathrm{F\&S}}_{\mathrm{p1}}$ using ER algorithms, we need to define the following:

$\widetilde{\mathrm{TP}}_{\mathrm{p1}}$, which represents the aggregated results obtained by aggregating sub criterion of pilot 1 Technical Proficiency (TP);

$\widetilde{\mathrm{PF}}_{\mathrm{p1}}$, which represents the aggregated results obtained by aggregating sub criterion of pilot 1 Personal Fatigue (PF);

$\widetilde{\mathrm{NTS}}_{\mathrm{p1}}$, which represents the aggregated results obtained by aggregating sub criterion of pilot 1 Non-Technical Skills (NTS); and

$\widetilde{\mathrm{F\&S}}_{\mathrm{p1}}$, which represents the aggregated results obtained by aggregating sub criterion of pilot 1 Fitness & Strength (F&S).

Based on the given fuzzy aggregated results of TP, PF, NTS and F&S for Pilot 1, the results from the mapping process are as follows:

$\widetilde{TP}_{P1}$ ={(0.03, V. Good), (0.12, Good), (0.33, Average), (0.41, Low), (0.10, Basic)}

$\widetilde{PF}_{P1}$ ={(0.07, Neutral), (0.26, S. Fatigued), (0.28, Moderate), (0.19, Fatigued), (0.20, V. Bad)}

$\widetilde{NTS}_{P1}$ ={(0.09, V. Good), (0.21, Good), (0.52, Moderate), (0.13, Bad), (0.06, V. Bad)}

$\widetilde{F\&S}_{P1}$ ={(0.94, Fit), (0.04, Good), (0.02, Moderate), (0, Bad), (0, Unfit)}

The global weights obtained by ANP are as follows:

ω_{TP}= 0.045, ω_{PF}= 0.186, ω_{NTS}= 0.606, and $\omega_{F\&S}$= 0.163

Where:

ω_{TP}, is the global weight assigned for PR-TP;

ω_{PF}, is the global weight assigned for PR-PF;

ω_{NTS}, represents the global weight assigned for PR-NTS; and

$\omega_{F\&S}$, represents the global weight assigned for PR-F&S.

The sum of TP, PF, NTS and F&S are as follows:

$\omega_{TP} + \omega_{PF} + \omega_{NTS} + \omega_{F\&S} =$ 0.045 + 0.186 + 0.606+ 0.163= 1.

The aggregation process of the first two criterion of PR, $\widetilde{TP}_{p1}$ and $\widetilde{PF}_{p1}$, are as follows:

M_1^mrepresents the subset $\widetilde{TP}_{p1}$, and M_2^m represent the subset $\widetilde{PF}_{p1}$. Using ER equation (6.4), can obtain the followings:

$M_1^m = \omega_{TP}\beta_1^m$, where ($m$ = 1,2,3,4,5)

$M_2^m = \omega_{PF}\beta_2^m$, where ($m$ = 1,2,3,4,5)

As a result, the following table has been constructed:

When, m= 1, M_1^1= 0.045×0.03 = 0.002, M_2^1= 0.186×0.07 = 0.013

m= 2, M_1^2= 0.045×0.12 = 0.005, M_2^2= 0.186×0.26 = 0.049

m= 3, M_1^3= 0.045×0.33 = 0.015, M_2^3= 0.186×0.28 = 0.052

m= 4, M_1^4= 0.045×0.41 = 0.019, M_2^4= 0.186×0.19 = 0.035

m= 5, M_1^5= 0.045×0.10 = 0.005, M_2^5= 0.186×0.20 = 0.037

When $M_{H_{TP}}$ represents the individual remaining belief for $\mathrm{M}_1^{\mathrm{m}}$, and $M_{H_{PF}}$ represents the individual remaining belief for $\mathrm{M}_2^{\mathrm{m}}$, therefore, equation 6.5, can be applied as follows:

- $M_{H_{TP}} = \bar{M}_{H_{TP}} + \widetilde{M}_{H_{TP}}$
- $M_{H_{PF}} = \bar{M}_{H_{PF}} + \widetilde{M}_{H_{PF}}$

$\bar{M}_{H_{TP}}, \widetilde{M}_{H_{TP}}$, and $\bar{M}_{H_{PF}}\widetilde{M}_{H_{PF}}$ can be found by applying equations (6.6-6.7), as follow:

- $\bar{M}_{H_{TP}} = 1 - \omega_{TP}$ =1- 0.045 = 0.955
- $\bar{M}_{H_{PF}} = 1 - \omega_{PF}$ =1- 0.186= 0.814
- $\widetilde{M}_{H_{TP}} = \omega_{TP}(1 - \sum_{m}^{5} \beta_1^m)$ = 0.955× (1- (0.03+0.12+0.33+0.41+0.10)) = 0
- $\widetilde{M}_{H_{PF}} = \omega_{PF}(1 - \sum_{m}^{5} \beta_2^m)$ = 0.814× (1- (0.07+0.26+0.28+0.19+0.20)) = 0
- $M_{H_{TP}} = \bar{M}_{H_{TP}} + \widetilde{M}_{H_{TP}}$ = 0.955+0= 0.955
- $M_{H_{PF}} = \bar{M}_{H_{PF}} + \widetilde{M}_{H_{PF}}$ = 0.814+0= 0.814

By using equations (6.8-6.11), to find $\beta^{m'} = k\left(M_1^m M_2^m + M_1^m M_{H_{PF}} + M_2^m M_{H_{TP}}\right)^{-1}$, ($\bar{M}'_{H_U}$), and ($\widetilde{M}'_{H_U}$), first we need to find k using equation (6.8):

$k = [1 - \sum_{T=1}^{5} \sum_{R=1\neq T}^{5} M_1^T M_2^R]^{-1}$

$$k = \left(1 - \begin{array}{ccccc} - + & M_1^1 M_2^2 + & M_1^1 M_2^3 + & M_1^1 M_2^4 + & M_1^1 M_2^5 + \\ M_1^2 M_2^1 + & - + & M_1^2 M_2^3 + & M_1^2 M_2^4 + & M_1^2 M_2^5 + \\ M_1^3 M_2^1 + & M_1^3 M_2^2 + & - + & M_1^3 M_2^4 + & M_1^3 M_2^5 + \\ M_1^4 M_2^1 + & M_1^4 M_2^2 + & M_1^4 M_2^3 + & - + & M_1^4 M_2^5 + \\ M_1^5 M_2^1 + & M_1^5 M_2^2 + & M_1^5 M_2^3 + & M_1^5 M_2^4 + & - \end{array} \right)^{-1}$$

$$k = \big(1 - (- + (0.002 \times 0.049) + (0.002 \times 0.052) + (0.002 \times 0.035) + (0.002 \times 0.037) + (0.005 \times 0.013) + - + (0.005 \times 0.052) + (0.005 \times 0.035) + (0.005 \times 0.037) + (0.015 \times 0.013) + (0.015 \times 0.049) + - + (0.015 \times 0.035) + (0.015 \times 0.037) + (0.019 \times 0.013) + (0.019 \times 0.049) + (0.019 \times 0.052) + - + (0.049 \times 0.037) + (0.005 \times 0.013) + (0.005 \times 0.049) + (0.005 \times 0.052) + (0.005 \times 0.035) + -)\big)^{-1}$$

$$k = \left(1 - \begin{array}{ccccc} - + & 0 + & 0 + & 0 + & 0 + \\ 0 + & - + & 0 + & 0 + & 0 + \\ 0 + & 0.001 + & - + & 0.001 + & 0.001 + \\ 0 + & 0.001 + & 0.001 + & - + & 0.001 + \\ 0 + & 0 + & 0 + & 0 + & - \end{array} \right)^{-1}$$

k= 1.007

Then, before using equations (6.12-6.13) to find (β^m) and (M_{H_U}), we need to utilise equations (6.8-6.11), to find ($\beta^{m'}$), ($\bar{M}'_{H_U}$), and ($\tilde{M}'_{H_U}$), as follow:

$\bar{M}'_{H_U} = K(\bar{M}_{H_{TP}} \bar{M}_{H_{PF}})$ = 1.007× 0.955× 0.814= 0.783

$\tilde{M}'_{H_U} = K(\tilde{M}_{H_{TP}} \tilde{M}_{H_{PF}} + \tilde{M}_{TP} \bar{M}_{H_{PF}} + \bar{M}_{H_{TP}} \tilde{M}_{H_{PF}})$ =

1.007×[(0×0)+(0.955×0)+(0×0.814)]=0

Accordingly, when $\beta^m = \frac{\beta^{m'}}{(1-\bar{H}_U)}$ $, where\ (m = $ 1,2,3,4,5), then:

$\beta^{m'} = k\big(M_1^m M_2^m + M_1^m M_{H_{PF}} + M_2^m M_{H_{TP}}\big)$

$\beta^{1'} = k\big(M_1^1 M_2^1 + M_1^1 M_{H_{PF}} + M_2^1 M_{H_{TP}}\big) =$

1.007×[(0.002×0.013)+(0.002×0.814)+(0.955×0.013)]= 0.013

$\beta^{2'} = k\left(M_1^2 M_2^2 + M_1^2 M_{H_{PF}} + M_2^2 M_{H_{TP}}\right) =$

1.007×[(0.005×0.049)+(0.005×0.814)+(0.955×0.049)] = 0.052

$\beta^{3'} = k\left(M_1^3 M_2^3 + M_1^3 M_{H_{PF}} + M_2^3 M_{H_{TP}}\right) =$

1.007×[(0.015×0.052)+(0.015×0.814)+(0.955×0.052)] = 0.063

$\beta^{4'} = k\left(M_1^4 M_2^4 + M_1^4 M_{H_{PF}} + M_2^4 M_{H_{TP}}\right) =$

1.007×[(0.019×0.035)+(0.019×0.814)+(0.955×0.035)]= 0.050

$\beta^{5'} = k\left(M_1^5 M_2^5 + M_1^5 M_{H_{PF}} + M_2^5 M_{H_{TP}}\right) =$

1.007×[(0.005×0.037)+(0.005×0.814)+(0.955×0.037)]= 0.039

From the above aggregations, the obtained results $\beta^{1'}$, $\beta^{2'}$,$\beta^{3'}$,$\beta^{4'}$, and $\beta^{5'}$represent M_{12}^1, M_{12}^2, M_{12}^3, M_{12}^4, and $M_{12}^5$for the first two aggregations. These will be used with the third aggregation similar to the above aggregation process. The following are the aggregation of the criterion NTS with the aggregated result from TP and PF:

M_{12}^m represents the aggregated subset of $\widetilde{TP}_{p1}$, and $\widetilde{PF}_{p1}$, while M_3^m represents the subset $\widetilde{NTS}_{p1}$. Using the ER equation (6.6) can obtain the following:

$M_3^m = \omega_{NTS}\beta_3^m$,   where ($m$ = 1,2,3,4,5)

When, m= 1, M_{12}^1= 0.013, M_3^1= 0.606×0.09 = 0.055

m= 2, M_{12}^2= 0.052, M_3^2= 0.606×0.21 = 0.127

m= 3, M_{12}^3= 0.063, M_3^3= 0.606×0.52 = 0.313

m= 4, M_{12}^4= 0.050, M_3^4= 0.606×0.13 = 0.076

m= 5, M_{12}^5= 0.039, M_3^5= 0.606×0.06 = 0.034

When $M_{H_{12}}$ represents the individual remaining belief for $\mathrm{M}_{12}^{\mathrm{m}}$, and $M_{H_{NTS}}$ represents the individual remaining belief for $\mathrm{M}_3^{\mathrm{m}}$, equation 6.7 can be applied as follows:

- $M_{H_{NTS}} = \bar{M}_{H_{NTS}} + \widetilde{M}_{H_{NTS}}$

$\bar{M}_{H_{NTS}}$, $\widetilde{M}_{H_{NTS}}$ can be found by applying equations (6.8-6.9) as follows:

- $\overline{M}_{H_{NTS}} = 1 - \omega_{NTS}$ = 1- 0.606= 0.394
- $\widetilde{M}_{H_{NTS}} = \omega_{NTS}(1 - \sum_{m}^{5} \beta_3^m)$ = 0.606× (1- (0.09+0.21+0.52+0.13+0.06))= 0
- $M_{H_{NTS}} = \overline{M}_{H_{NTS}} + \widetilde{M}_{H_{NTS}}$ = 0.394+0= 0.394

By using equations (6.10-6.13) to find $\beta^{m'} = k\left(M_{12}^m M_3^m + M_{12}^m M_{H_{NTS}} + M_3^m M_{H_{12}}\right)^{-1}$, ($\overline{M}'_{H_U}$), and ($\widetilde{M}'_{H_U}$), we find k using equation (6.13):

$k = [1 - \sum_{T=1}^{5} \sum_{R=1 \neq T}^{5} M_{12}^T M_3^R]^{-1}$

$$k = \left(1 - \begin{array}{ccccc} -+ & M_{12}^1 M_3^2 + & M_{12}^1 M_3^3 + & M_{12}^1 M_3^4 + & M_{12}^1 M_3^5 + \\ M_{12}^2 M_3^1 + & -+ & M_{12}^2 M_3^3 + & M_{12}^2 M_3^4 + & M_{12}^2 M_3^5 + \\ M_{12}^3 M_3^1 + & M_{12}^3 M_3^2 + & -+ & M_{12}^3 M_3^4 + & M_{12}^3 M_3^5 + \\ M_{12}^4 M_3^1 + & M_{12}^4 M_3^2 + & M_{12}^4 M_3^3 + & -+ & M_{12}^4 M_3^5 + \\ M_{12}^5 M_3^1 + & M_{12}^5 M_3^2 + & M_{12}^5 M_3^3 + & M_{12}^5 M_3^4 + & - \end{array} \right)^{-1}$$

$$k = \big(1 - (- + (0.013 \times 0.127) + (0.013 \times 0.313) + (0.013 \times 0.076) + (0.013 \times 0.034) + (0.052 \times 0.055) + - + (0.052 \times 0.313) + (0.052 \times 0.076) + (0.052 \times 0.034) + (0.063 \times 0.055) + (0.063 \times 0.127) + - + (0.063 \times 0.076) + (0.063 \times 0.034) + (0.050 \times 0.055) + (0.050 \times 0.127) + (0.050 \times 0.313) + - + (0.050 \times 0.034) + (0.039 \times 0.055) + (0.039 \times 0.127) + (0.039 \times 0.313) + (0.039 \times 0.076) + -)\big)^{-1}$$

$$k = \left(1 - \begin{array}{ccccc} -+ & 0.002 + & 0.004 + & 0.001 + & 0 + \\ 0.003 + & -+ & 0.016 + & 0.004 + & 0.002 + \\ 0.003 + & 0.008 + & -+ & 0.005 + & 0.002 + \\ 0.003 + & 0.006 + & 0.016 + & -+ & 0.002 + \\ 0.002 + & 0.005 + & 0.012 + & 0.003 + & - \end{array} \right)^{-1}$$

k= 1.111

Before using equations (6.13-6.15) to find (β^m) and (M_{H_U}), we need to utilise equations (6.11-6.12) to find ($\beta^{m'}$), ($\overline{M}'_{H_U}$), and ($\widetilde{M}'_{H_U}$):

$\overline{M}'_{H_U} = k\left(\overline{M}_{H_{12}} \overline{M}_{H_{NTS}}\right)$ = 1.111× 0.783× 0.394= 0.346

$\widetilde{M}'_{H_U} = k\left(\widetilde{M}_{H_{12}}\widetilde{M}_{H_{NTS}} + \widetilde{M}_{H_{12}}\overline{M}_{H_{NTS}} + \widetilde{M}_{H_{NTS}}\overline{M}_{H_{12}}\right)$ =

1.111×[(0×0.394)+(0.783×0)+(0×0.394)] = 0

Accordingly, when $\beta^m = \frac{\beta^{m'}}{(1-\bar{H}_U)}, where\ (m = 1,2,3,4,5)$, then:

$\beta^m = \frac{\beta^{m'}}{(1-\bar{H}_U)}$ $, where\ (m = 1,2,3,4,5)$, then:

$\beta^{m'} = k\left(M_{12}^m M_3^m + M_{12}^m M_{H_{NTS}} + M_3^m M_{H_{12}}\right)$

$\beta^{1'} = k\left(M_{12}^1 M_3^1 + M_{12}^1 M_{H_{NTS}} + M_3^1 M_{H_{12}}\right)$ =

1.111×[(0.013×0.055)+(0.013×0.394)+(0.783×0.055)]= 0.055

$\beta^{2'} = k\left(M_{12}^2 M_3^2 + M_{12}^2 M_{H_{NTS}} + M_3^2 M_{H_{12}}\right)$ =

1.111×[(0.052×0.127)+(0.052×0.394)+(0.783×0.127)] = 0.140

$\beta^{3'} = k\left(M_{12}^3 M_3^3 + M_{12}^3 M_{H_{NTS}} + M_3^3 M_{H_{12}}\right)$ =

1.111×[(0.063×0.313)+(0.063×0.394)+(0.783×0.313)] = 0.322

$\beta^{4'} = k\left(M_{12}^4 M_3^4 + M_{12}^4 M_{H_{NTS}} + M_3^4 M_{H_{12}}\right)$ =

1.111×[(0.050×0.076)+(0.050×0.394)+(0.783×0.076)]= 0.092

$\beta^{5'} = k\left(M_{12}^5 M_3^5 + M_{12}^5 M_{H_{NTS}} + M_3^5 M_{H_{12}}\right)$ =

1.111×[(0.039×0.034)+(0.039×0.394)+(0.783×0.034)]= 0.048

From the above aggregations, the obtained results $\beta^{1'}$, $\beta^{2'}$,$\beta^{3'}$,$\beta^{4'}$, and $\beta^{5'}$represent M_{123}^1, M_{123}^2, M_{123}^3, M_{123}^4, and $M_{123}^5$for the first three aggregations. These will be used with the fourth aggregation similar to the above aggregation process. The following are the aggregation of the criterion F&S with the aggregated result from TP, PF and NTS:

M_{123}^m represents the aggregated subset of $\widetilde{TP}_{p1}$, $\widetilde{PF}_{p1}$ and $\widetilde{NTS}_{p1}$, while M_4^m represents the subset $\widetilde{\text{F\&S}}_{p1}$. Using the ER equation (6.6) can obtain the following:

$M_4^m = \omega_{\text{F\&S}}\beta_4^m$, where ($m$ = 1,2,3,4,5)

When, m= 1, M_{123}^1= 0.055, M_4^1= 0.163×0.94= 0.153

m= 2, M_{123}^{2}= 0.140, M_{4}^{2}= 0.163×0.04= 0.007

m= 3, M_{123}^{3}= 0.322, M_{4}^{3}= 0.163×0.02= 0.003

m= 4, M_{123}^{4}= 0.092, M_{4}^{4}= 0.163×0 = 0

m= 5, M_{123}^{5}= 0.048, M_{4}^{5}= 0.163×0= 0

When $M_{H_{123}}$ represents the individual remaining belief for $\mathrm{M}_{123}^{\mathrm{m}}$, and $M_{H_{F\&S}}$ represents the individual remaining belief for $\mathrm{M}_{4}^{\mathrm{m}}$, equation 6.7 can be applied as follows:

- $M_{H_{\mathrm{F\&S}}} = \bar{M}_{H_{\mathrm{F\&S}}} + \widetilde{M}_{H_{\mathrm{F\&S}}}$

$\bar{M}_{H_{\mathrm{F\&S}}}, \widetilde{M}_{H_{\mathrm{F\&S}}}$ can be found by applying equations (6.8-6.9) as follows:

- $\bar{M}_{H_{\mathrm{F\&S}}} = 1 - \omega_{\mathrm{F\&S}}$ = 1- 0.163= 0.837
- $\widetilde{M}_{H_{\mathrm{F\&S}}} = \omega_{\mathrm{F\&S}}(1 - \sum_{m}^{5} \beta_{4}^{m})$ = 0.163× (1- (0.94+0.04+0.02+0+0))= 0
- $M_{H_{\mathrm{F\&S}}} = \bar{M}_{H_{\mathrm{F\&S}}} + \widetilde{M}_{H_{\mathrm{F\&S}}}$ = 0.837+0= 0.837

By using equations (6.10-6.13) to find $\beta^{m'} = k\left(M_{123}^{m} M_{4}^{m} + M_{123}^{m} M_{H_{\mathrm{F\&S}}} + M_{4}^{m} M_{H_{123}}\right)^{-1}$, $(\bar{M}'_{H_U})$, and $(\widetilde{M}'_{H_U})$, we find k using equation (6.13):

$$k = [1 - \sum_{T=1}^{5} \sum_{R=1 \neq T}^{5} M_{123}^{T} M_{4}^{R}]^{-1}$$

$$k = \left(1 - \begin{array}{ccccc} - + & M_{123}^{1} M_{4}^{2} + & M_{123}^{1} M_{4}^{3} + & M_{123}^{1} M_{4}^{4} + & M_{123}^{1} M_{4}^{5} + \\ M_{123}^{2} M_{4}^{1} + & - + & M_{123}^{2} M_{4}^{3} + & M_{123}^{2} M_{4}^{4} + & M_{123}^{2} M_{4}^{5} + \\ M_{123}^{3} M_{4}^{1} + & M_{123}^{3} M_{4}^{2} + & - + & M_{123}^{3} M_{4}^{4} + & M_{123}^{3} M_{4}^{5} + \\ M_{123}^{4} M_{4}^{1} + & M_{123}^{4} M_{4}^{2} + & M_{123}^{4} M_{4}^{3} + & - + & M_{123}^{4} M_{4}^{5} + \\ M_{123}^{5} M_{4}^{1} + & M_{123}^{5} M_{4}^{2} + & M_{123}^{5} M_{4}^{3} + & M_{123}^{5} M_{4}^{4} + & - \end{array} \right)^{-1}$$

$$k = \big(1 - (- + (0.055 \times 0.007) + (0.055 \times 0.003) + (0.055 \times 0) + (0.055 \times 0) + (0.140 \times 0.153) + - + (0.140 \times 0.003) + (0.140 \times 0) + (0.140 \times 0) + (0.322 \times 0.153) + (0.322 \times 0.007) + - + (0.322 \times 0) + (0.322 \times 0) + (0.092 \times 0.153) + (0.092 \times 0.007) + (0.092 \times 0.003) + - + (0.092 \times 0) + (0.048 \times 0.153) + (0.048 \times 0.007) + (0.048 \times 0.003) + (0.048 \times 0) + -)\big)^{-1}$$

$$k = \left(1 - \begin{matrix} - + & 0 + & 0 + & 0 + & 0 + \\ 0.022 + & - + & 0 + & 0 + & 0 + \\ 0.049 + & 0.002 + & - + & 0 + & 0 + \\ 0.014 + & 0.001 + & 0 + & - + & 0 + \\ 0.007 + & 0 + & 0 + & 0 + & - \end{matrix} \right)^{-1}$$

k= 1.107

Before using equations (6.13-6.15) to find (β^m) and (M_{H_U}), we need to utilise equations (6.11-6.12) to find ($\beta^{m\prime}$), ($\bar{M}'_{H_U}$), and ($\tilde{M}'_{H_U}$):

$\bar{M}'_{H_U} = k\left(\bar{M}_{H_{123}}\bar{M}_{H_{\text{F\&S}}}\right)$ = 1.107× 0.346× 0.837= 0.317

$\tilde{M}'_{H_U} = k\left(\tilde{M}_{H_{123}}\tilde{M}_{H_{\text{F\&S}}} + \tilde{M}_{H_{123}}\bar{M}_{H_{\text{F\&S}}} + \tilde{M}_{H_{\text{F\&S}}}\bar{M}_{H_{123}}\right)$ =

1.107×[(0×0)+(0.342×0)+(0×0.837)] = 0

Accordingly, when $\beta^m = \frac{\beta^{m\prime}}{(1-\bar{H}_U)}, where\ (m =$ 1,2,3,4,5), then:

$\beta^m = \frac{\beta^{m\prime}}{(1-\bar{H}_U)}\ , where\ (m =$ 1,2,3,4,5), then:

$\beta^{m\prime} = k\left(M^m_{123}M^m_4 + M^m_{123}M_{H_{\text{F\&S}}} + M^m_4 M_{H_{123}}\right)$

$\beta^{1\prime} = k\left(M^1_{123}M^1_4 + M^1_{123}M_{H_{\text{F\&S}}} + M^1_4 M_{H_{123}}\right)$ =

1.107×[(0.055×0.153)+(0.055×0.837)+(0.342×0.153)]= 0.118

$\beta^{2\prime} = k\left(M^2_{123}M^2_4 + M^2_{123}M_{H_{\text{F\&S}}} + M^2_4 M_{H_{123}}\right)$ =

1.107×[(0.140×0.007)+(0.140×0.837)+(0.342×0.007)] = 0.134

$\beta^{3\prime} = k\left(M^3_{123}M^3_4 + M^3_{123}M_{H_{\text{F\&S}}} + M^3_4 M_{H_{123}}\right)$ =

1.107×[(0.322×0.003)+(0.322×0.837)+(0.342×0.003)] = 0.300

$\beta^{4\prime} = k\left(M^4_{123}M^4_4 + M^4_{123}M_{H_{\text{F\&S}}} + M^4_4 M_{H_{123}}\right)$ =

1.107×[(0.092×0)+(0.092×0.837)+(0.342×0)]= 0.086

$\beta^{5\prime} = k\left(M^5_{123}M^5_4 + M^5_{123}M_{H_{\text{F\&S}}} + M^5_4 M_{H_{123}}\right)$ =

1.107×[(0.048×0)+(0.048×0.837)+(0.342×0)]= 0.045

Accordingly, $\beta^1, \beta^2, \beta^3, \beta^4, and\ \beta^5$can be found using equation (6.14) as follows:

When, $m = 1,\ then\ \frac{\beta^{1'}}{1-\bar{H}'_U} = \frac{0.118}{1-0.317} = 0.17$

When, $m = 2,\ then\ \frac{\beta^{2'}}{1-\bar{H}'_U} = \frac{0.134}{1-0.317} = 0.20$

When, $m = 3,\ then\ \frac{\beta^{3'}}{1-\bar{H}'_U} = \frac{0.300}{1-0.317} = 0.44$

When, $m = 4,\ then\ \frac{\beta^{4'}}{1-\bar{H}'_U} = \frac{0.086}{1-0.317} = 0.13$

When, $m = 5,\ then\ \frac{\beta^{5'}}{1-\bar{H}'_U} = \frac{0.045}{1-0.317} = 0.07$

Furthermore, finding M_{H_U} can be done using equation (6.15) as follows:

$M_{H_U} = \frac{\tilde{M}'_{H_U}}{1- \bar{M}'_{H_U}} = \frac{0}{1-0.317} = 0$

As a result, the aggregation of PR main criterion for pilot 1 can be presented as follows (see Table 6.19):

PR_{P1} ={(17% V. High), (20% High), (44% Moderate), (13% Low), (7% V. Low)}

II.2 Pilot 2

II.2.1 Mapping process for lower-level MPRIs

Based on the information given for each pilot presented on Table 6.1 (see section 6.4), the generic model on Figure 6.2 (see section 6.4.1) and the linguistic terms used for assessment presented on Table 6.2 (see section 6.4.1), the following are the mapping process from the lower-level MPRIs. This followed by the mapping process from the main criterion towards the goal in the following section.

II.2.1.1 Working hours (PF-WH)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 2's WH is as follows:

$$\widetilde{WH}_{p2} = \{(V.Good, 0), (Good, 0.30), (Moderate, 0.70), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed on the fuzzy rules in Table (II.1) for mapping pilots' WH to its associated criterion, PF, in order to assess pilot reliability based on WH.

Table II.1 Fuzzy rule base belief structure for PF-WH

Working Hours (WH) to Personal Fatigue (PF)	R^1: if WH assessed 'V. Good', then 100% 'Neutral' R^2: if WH assessed 'Good', then 80% 'S. Fatigued' and 20% 'Neutral' R^3: if WH assessed 'Moderate', then 80% 'Moderate' and 20% 'S. Fatigued' R^4: if WH assessed 'Bad', then 80% 'Fatigued' and 20% 'V. Bad' R^5: if WH assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping WH to PF can be conducted based on given information from Pilot 2 and subject to the fuzzy rules from Table II.1. They are as follows:

Based on R^2 and R^3, the result can transform into 0.06 Neutral ($O^1 = 0.3 \times 0.2$), 0.38 S. Fatigued ($O^2 = (0.3 \times 0.8) + (0.7 \times 0.2)$), and 0.56 Moderate ($O^3 = 0.7 \times 0.8$), respectively. Therefore, the WH for Pilot 2 is assessed as follows:

$$PF - WH_{p2}$$
$$= \{(Neutral, 0.06), (S.Fatigued, 0.38), (Moderate, 0.56), (Fatigued, 0), (V.Bad, 0)$$

II.2.2.2 Working stresses (PF-WS)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 2's WS is as follows:

$$\widetilde{WS}_{p2} = \{(V.Low, 0), (Low, 0), (Moderate, 0), (High, 0.4), (V.High, 0.6)\}$$

The harbour masters at this port have agreed on the fuzzy rules from Table (II.2) for mapping pilots' WS to its associated criterion, PF, in order to assess pilot reliability based on WS.

Table II.2 Fuzzy rule base belief structure for PF-WS

Working Stresses (WS) to Personal Fatigue (PF)	R^1: if WS assessed 'V. Low', then 100% 'Neutral' R^2: if WS assessed 'Low', then 90% 'S. Fatigued' and 10% 'Moderate' R^3: if WS assessed 'Moderate', then 80% 'Moderate' and 20% 'Fatigued' R^4: if WS assessed 'High', then 80% 'Fatigued' and 20% 'V. Bad' R^5: if WS assessed 'V. High', then 100% 'V. Bad'

The fuzzy outputs from mapping WS to PF, conducted based on given information for Pilot 2 and subject to fuzzy rules from Table II.2, are as follow:

Based on R^4 and R^5, the result can transform into 0.32 Fatigued ($O^4 = 0.4 \times 0.8$), and 0.68 V. Bad ($O^5 = (0.4 \times 0.2) + (0.6 \times 1)$), respectively. Therefore, the WS for Pilot 2 is assessed as follows:

$$PF - WS_{p2} = \{(Neutral, 0), (S.Fatigued, 0), (Moderate, 0), (Fatigued, 0.32), (V.Bad, 0.68)\}$$

II.2.2.3 Working environment (PF-WEnv)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 2's WEnv is as follows:

$$\widetilde{WEnv}_{p2} = \{(V.Good, 0), (Good, 0), (Moderate, 0.5), (Bad, 0.5), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules of Table (II.3) for mapping pilots' WEnv to its associated criterion, PF, in order to assess pilot reliability based on WS.

Table II.3 Fuzzy rule base belief structure for PF-WEnv

Working Environment (WEnv) to Personal Fatigue (PF)	R^1: if WEnv assessed ‘V. Good’, then 100% ‘Neutral’ R^2: if WEnv assessed ‘Good’, then 80% ‘S. Fatigued’ and 20% ‘Moderate’ R^3: if WEnv assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘Fatigued’ R^4: if WEnv assessed ‘Bad’, then 80% ‘Fatigued’ and 20% ‘V. Bad’ R^5: if WEnv assessed ‘V. Bad’, then 100% ‘V. Bad’

The fuzzy outputs from mapping WEnv to PF, conducted based on given information from Pilot 2 and subject to fuzzy rules from Table II.3, are as follow:

Based on R^3 and R^4 , the result can transform into 0.40 Moderate ($O^3 = 0.5 \times 0.8$), 0.50 Fatigued ($O^4 = (0.5 \times 0.2) + (0.5 \times 0.8)$), and 0.10 V. Bad ($O^5 = 0.5 \times 0.2$), respectively. Therefore, the WEnv for Pilot 2 is assessed as follows:

$$PF - WEnv_{p2}$$
$$= \{(Neutral, 0), (S.Fatigued, 0), (Moderate, 0.40), (Fatifued, 0.50), (V.Bad, 0.1)\}$$

II.2.2.4 Decision-making (NTS-DM)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 2’s DM is as follows:

$$\widetilde{DM}_{p2} = \{(V.Good, 0), (Good, 0.2), (Average, 0.8), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules from Table (II.4) for mapping pilots’ DM to its associated criterion, NTS, in order to assess pilot reliability based on DM.

Table II.4 Fuzzy rule base belief structure for NTS-DM

Decision Making (DM) to Non-technical Skills (NTS)	R^1: if DM assessed ‘V. Good’, then 100% ‘V. Good’ R^2: if DM assessed ‘Good’, then 80% ‘Skilful’ and 20% ‘V. Good’ R^3: if DM assessed ‘Average’, then 90% ‘Moderate’ and 10% ‘Bad’ R^4: if DM assessed ‘Bad’, then 80% ‘Bad’ and 20% ‘V. Bad’ R^5: if DM assessed ‘V. Bad’, then 100% ‘V. Bad’

The fuzzy outputs from mapping DM to NTS, conducted based on given information from Pilot 2 and subject to fuzzy rules from Table II.4, are as follows:

Based on R^2andR^3, the result can transform into 0.04 V. Good ($O^1 = 0.2 \times 0.2$), 0.16 Good ($O^2 = 0.2 \times 0.8$), 0.72 Moderate ($O^3 = 0.8 \times 0.9$), and 0.08 Bad ($O^4 = 0.8 \times 0.1$), respectively. Therefore, the DM for Pilot 2 is assessed as follows:

$$NTS - DM_{p2}$$
$$= \{(V.Good, 0.04), (Good, 0.16), (Moderate, 0.72), (Bad, 0.08), (V.Bad, 0)\}$$

II.2.2.5 Situation awareness (NTS-SA)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 2's SA is as follows:

$$\widetilde{SA}_{p2} = \{(V.Good, 0), (Good, 0.6), (Average, 0.4), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.5) for mapping pilots' SA to its associated criterion, NTS, in order to assess pilot reliability based on SA.

Table II.5 Fuzzy rule base belief structure for NTS-SA

Situation Awareness (SA) to Non-technical Skills (NTS)	R^1: if SA assessed 'V. Good', then 100% 'V. Good' R^2: if SA assessed 'Good', then 80% 'Skilful' and 20% 'V .Good' R^3: if SA assessed 'Average', then 90% 'Moderate' and 10% 'Bad' R^4: if SA assessed 'Bad', then 80% 'Bad' and 20% 'V. Bad' R^5: if SA assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping SA to NTS, conducted based on given information for Pilot 2 and subject to fuzzy rules from Table II.5, are as follows:

Based on R^2andR^3, the result can transform into 0.12 V. Good ($O^1 = 0.6 \times 0.2$), 0.48 Good ($O^2 = 0.6 \times 0.8$), 0.36 Moderate ($O^3 = 0.4 \times 0.9$), and 0.04 Bad ($O^4 = 0.4 \times 0.1$), respectively. Therefore, the SA for Pilot 2 is assessed as follows:

$$NTS - SA_{p2} = \{(V.Good, 0.12), (Good, 0.48), (Moderate, 0.36), (Bad, 0.04), (V.Bad, 0)\}.$$

II.2.2.6 Communication skills (NTS-CS)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 2’s CS is as follows:

$$\widetilde{CS}_{p2} = \{(V.Good, 0), (Good, 0.2), (Average, 0.8), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.6) for mapping pilots’ CS to its associated criterion, NTS, in order to assess pilot reliability based on CS.

Table II.6 Fuzzy rule base belief structure for NTS- CS

Communication Skills (CS) to Non-technical Skills (NTS)	R^1: if CS assessed ‘V. Good’, then 100% ‘V. Good’ R^2: if CS assessed ‘Good’, then 80% ‘Skilful’ and 20% ‘V. Good’ R^3: if CS assessed ‘Average’, then 90% ‘Moderate’ and 10% ‘Bad’ R^4: if CS assessed ‘Bad’, then 80% ‘Bad’ and 20% ‘V. Bad’ R^5: if CS assessed ‘V. Bad’, then 100% ‘V. Bad’

The fuzzy outputs from mapping CS to NTS, conducted based on given information for Pilot 2 and subject to fuzzy rules on table II.6, are as follows:

Based on R^2andR^3, the result can transform into 0.04 V. Good ($O^1 = 0.2 \times 0.2$), 0.16 Good ($O^2 = 0.2 \times 0.8$), 0.72 Moderate ($O^3 = 0.8 \times 0.9$), and 0.08 Bad ($O^4 = 0.8 \times 0.1$), respectively. Therefore, the CS for Pilot 2 is assessed as follows:

$$NTS - \mathrm{CS}_{p2} = \{(V.Good, 0.04), (Good, 0.16), (Moderate, 0.72), (Bad, 0.08), (V.Bad, 0)\}$$

II.2.2.7 Teamwork and leadership (NTS-T&L)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 2’s T&L is as follows:

$$\widetilde{T\&L}_{p2} = \{(V.Good, 0), (Good, 0.6), (Average, 0.4), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.7) for mapping pilots’ T&L to its associated criterion, NTS, in order to assess pilot reliability based on T&L.

Table II.7 Fuzzy rule base belief structure for NTS-T&L

Teamwork and Leadership (T&L) to Non-technical Skills (NTS)	R^1: if T&L assessed 'V. Good', then 100% 'V. Good' R^2: if T&L assessed 'Good', then 80% 'Skilful' and 20% 'V. Good' R^3: if T&L assessed 'Average', then 90% 'Moderate' and 10% 'Bad' R^4: if T&L assessed 'Bad', then 80% 'Bad' and 20% 'V. Bad' R^5: if T&L assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping T&L to NTS, conducted based on given information for Pilot 2 and subject to fuzzy rules on Table II.7, are as follows:

Based on R^2andR^3, the result can transform into 0.12 V. Good ($O^1 = 0.6 \times 0.2$), 0.48 Good ($O^2 = 0.6 \times 0.8$), 0.36 Moderate ($O^3 = 0.4 \times 0.9$), and 0.04 Bad ($O^4 = 0.4 \times 0.1$), respectively.Therefore, the T&L for Pilot 2 is assessed as follows:

$$NTS - T\&L_{p2} = \{(V.Good, 0.12), (Good, 0.48), (Moderate, 0.36), (Bad, 0.04), (V.Bad, 0)\}$$

II.2.2.8 Health Issues (F&S-HI)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 2's HI is as follows:

$$\widetilde{HI}_{p2} = \{(Healthy, 0), (Good, 0.8), (Moderate, 0.2), (Bad, 0), (Severe, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.8) for mapping pilots' HI to its associated criterion, F&S, in order to assess pilot reliability based on HI.

Table II.8 Fuzzy rule base belief structure for F&S-HI

Health Issue (HI) to Fitness and Strength (F&S)	R^1: if HI assessed 'Healthy', then 100% 'Fit' R^2: if HI assessed 'Good', then 90% 'Good' and 10% 'Moderate' R^3: if HI assessed 'Moderate', then 90% 'Moderate' and 10% 'Bad' R^4: if HI assessed 'Bad', then 80% 'Bad' and 20% 'Unfit' R^5: if HI assessed 'Severe', then 100% 'Unfit'

The fuzzy outputs from mapping 'HI' to F&S, conducted based on given information for Pilot 2 and subject to fuzzy rules on Table II.8, are as follows:

Based on R^2 and R^3, the result can transform into 0.72 Good ($O^2 = 0.8 \times 0.9$), 0.26 Moderate ($O^3 = (0.8 \times 0.1) + (0.2 \times 0.9)$), and 0.02 Bad ($O^4 = 0.2 \times 0.1$), respectively. Therefore, the HI for Pilot 2 is assessed as follows:

$$F\&S - HI_{p2} = \{(Fit, 0), (Good, 0.72), (Moderate, 0.26), (Bad, 0.02), (Unfit, 0)\}$$

II.2.2.9 Body strength (F&S-BS)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 2's BS is as follows:

$$\widetilde{BS}_{p2} = \{(Fit, 0), (Good, 0.7), (Moderate, 0.3), (Weake, 0), (V.Weake, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.9) for mapping pilots' BS to its associated criterion, F&S, in order to assess pilot reliability based on BS.

Table II.9 Fuzzy rule base belief structure for F&S-BS

Body Strength (BS) to Fitness and Strength (F&S)	R^1: if BS assessed 'Fit', then 100% 'Fit' R^2: if BS assessed 'Good', then 90% 'Good' and 10% 'Moderate' R^3: if BS assessed 'Moderate', then 90% 'Moderate' and 10% 'Bad' R^4: if BS assessed 'Weak', then 80% 'Bad' and 20% 'Unfit' R^5: if BS assessed 'V. Weak', then 100% 'Unfit'

The fuzzy outputs from mapping BS to F&S, conducted based on given information for Pilot 2 and subject to fuzzy rules on Table II.9, are as follows:

Based on R^2 and R^3, the result can transform into 0.63 Good($O^2 = 0.7 \times 0.9$), 0.34 Moderate ($O^3 = (0.7 \times 0.1) + (0.3 \times 0.9)$), and 0.03 Bad ($O^4 = 0.3 \times 0.1$), respectively. Therefore, the BS for Pilot 2 is assessed as follows:

$$F\&S - BS_{p2} = \{(Fit, 0), (Good, 0.63), (Moderate, 0.34), (Bad, 0.03), (Unfit, 0)\}$$

II.2.3 Transforming quantitative data into qualitative

II.2.3.1 Pilot’s qualification and pilotage licensing (TP-QPL)

The harbour masters at this port have assigned the following marks of value to fuzzy rules to evaluate pilot reliability based on the pilot's QPL:

1- If the pilot holds an approved diploma or a BSc in nautical science and an approved pilot license from the port authority, he will be given 50 per cent. The pilot must satisfy 100 per cent of the port's minimum requirements.

2- If the pilot holds an approved diploma with an approved certificate of competency class 4 (COC IIII) as a 3rd officer, he will be given 60 per cent. Therefore, the pilot is evaluated as 20 per cent at minimum and 80 per cent at second minimum requirement.

3- If the pilot holds an approved diploma with an approved certificate of competency class 3 (COC III) as a 2nd officer or BSc with an approved (COC IIII) as a 3rd officer, then he will be given 70 per cent. Therefore, the pilot is evaluated as 80 per cent at second minimum requirement and 20 per cent on average, which represent the third requirement.

4- If the pilot holds an approved diploma with an approved certificate of competency class 2 (COC II) as a 1st officer or BSc with an approved (COC III) as a 2nd officer, then he will be given 80%. Therefore, the pilot is evaluated as 80 per cent average and 20 per cent second higher requirement.

5- If the pilot holds an approved diploma with an approved certificate of competency class 1 (COC I) as a master mariner or BSc with an approved (COC II) as a 1st officer, then he will be given 90%. Therefore, the pilot is evaluated as 80 per cent second required qualification and 20 per cent uppermost.

6- If the pilot holds an approved BSc with an approved (COC I) as a master mariner, then he will be given 100%. Therefore, the pilot is evaluated as 100 per cent the uppermost requirement.

According to the given pilots' information, with reference to the above rules, Pilot 2's TP-QPL is assessed based on his QPL as follows:

$$\widetilde{QPL}_{p2} = \{(Uppermost, 0), (Second\ Higher, 0.2), (Average, 0.8), (Second\ Min., 0), (Min., 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.10) for mapping pilots' QPL to its associated criterion, TP, in order to assess pilot reliability based on QPL.

Table II.10 Fuzzy rule base belief structure for TP-QPL

Qualification and pilotage licensing (QPL) to Technical Proficiency (TP)	R^1: if QPL assessed 'Uppermost', then 100% 'V. Good' R^2: if QPL assessed '2nd Higher', then 80% 'Good' and 20% 'V. Good' R^3: if QPL assessed 'Average', then 80% 'Average' and 20% 'Good' R^4: if QPL assessed '2nd Min.', then 90% 'Low' and 10% 'Average' R^5: if QPL assessed 'Min', then 100% 'Basic'

The fuzzy outputs from mapping QPL to TP, conducted based on given information for Pilot 2 and subject to fuzzy rules on Table II.10, are as follow:

Based on R^2andR^3, the result can transform into 0.04 V. Good ($O^1 = 0.2 \times 0.2$), 0.32 Good ($O^2 = (0.2 \times 0.8) + (0.8 \times 0.2)$), and 0.64 Average ($O^3 = 0.8 \times 0.8$), respectively. Therefore, the QPL for Pilot 2 is assessed as follows:

$$TP - QPL_{p2} = \{(V.Good, 0.04), (Good, 0.32), (Average, 0.64), (Low, 0), (Basic, 0)\}$$

II.2.3.2 Pilot's special training (TP-ST)

Similar to the requirements of pilot qualifications required by the port authority, there are sets of minimum basic training courses that are also essential for a pilot to be endorsed. According to the port authority requirements, the following are compulsory basic training courses that a pilot must have when applying for a pilotage license:

1- Proficiency in Survival Craft (PSC);

2- Personal Survival Technique (PST);

3- Fire Prevention and Firefighting (FPF);
4- Elementary First Aid (EFA);
5- Advanced Fire Prevention and Firefighting (AFF).

The authority also recommends some extra training courses, but they are optional. These extra courses are:

1- Global Maritime Distress and Safety System (GMDSS) training;
2- Radar simulation training;
3- Advanced Pilot Training (APT) course;
4- Bridge Resource Management (BRM) training course;
5- Port State Control (PSC) training;
6- Ship-handling simulator.

According to the experts' opinions, having valid course certificates for more than nine courses makes one a 'well-trained' pilot. This information helps in developing the membership function used to evaluate pilots based on their ST. Accordingly, if the pilot holds one of these certificates, then 10 per cent will be given for each valid certificate; if the certificate is not valid, then 0 per cent is given. Based on the pilot's given information in the test case, the following are the training courses that Pilot 2 has:

1- Proficiency in survival craft (PSC) (Valid);
2- Personal survival technique (PST) (Valid);
3- Fire prevention and firefighting (FPFF) (Not Valid);
4- Elementary first aid (EFA) (Valid);
5- Advanced fire prevention and firefighting certificate (AFF) (Valid);
6- Ship-handling simulator certificate (Valid);
7- Global Maritime Distress and Safety System (GMDSS) certificate (Not Valid);
8- Advanced Pilot Training (APT) certificate (Valid);

Based on the pilot's stated valid training certificates, 60 per cent is given to Pilot 2. The membership function model constructed is shown in Figures (II.1).

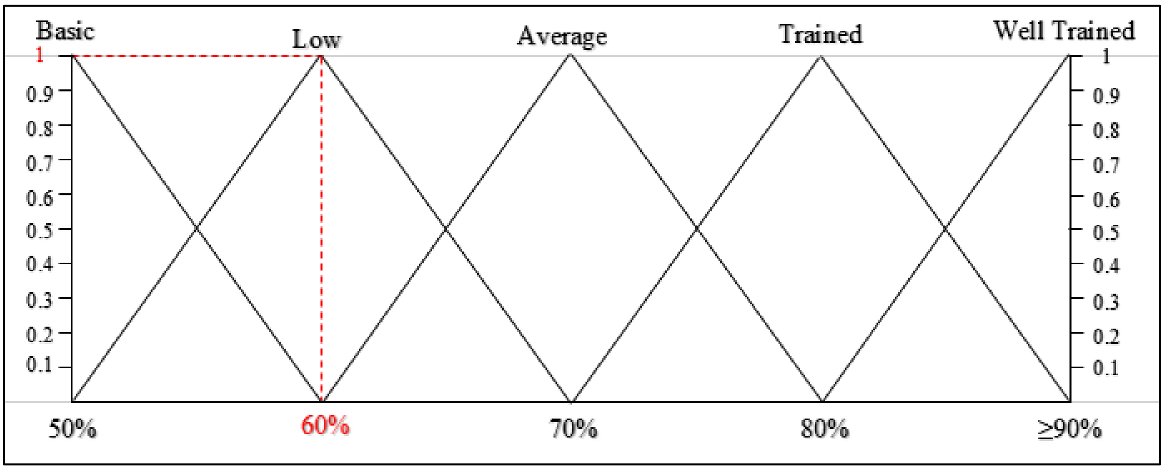

Figure II.1. The membership function for Pilot 2's special training (TP-ST)

The horizontal axis represents the quantitative number, while the vertical axis represents the belief degrees. When a given quantitative number is found not ranging between two different grades, then 100 per cent will be given. According to the given pilot's information, with reference to the above information, Pilot 2's TP-ST is assessed based on his ST as follows:

$$\widetilde{ST}_{\mathrm{p2}} = \{(Well\,Trained, 0), (Trained, 0), (Average, 0), (Low, 1), (Basic, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.11) for mapping pilots' ST to its associated criterion, TP, in order to assess pilot reliability based on ST.

Table II.11 Fuzzy rule base belief structure for TP-ST

Special Training (ST) to Technical Proficiency (TP)	R^1: if ST assessed 'Well Trained', then 100% 'V. Good' R^2: if ST assessed 'Trained', then 80% 'Good' and 20% 'V. Good' R^3: if ST assessed 'Average', then 80% 'Average' and 20% 'Good' R^4: if ST assessed 'Low', then 80% 'Low' and 20% 'Average' R^5: if ST assessed 'Basic', then 100% 'Basic'

The fuzzy outputs from mapping ST to TP, conducted based on given information for Pilot 2 and subject to fuzzy rules on Table II.11, are as follows:

Based on R^4 the result can transform into 0.2 V. Average ($O^3 = 1 \times 0.2$), and 0.8 Low ($O^4 = 1 \times 0.8$), respectively. Therefore, the ST for Pilot 2 is assessed as follows:

$$TP - ST_{p2} = \{(V.Good, 0), (Good, 0), (Average, 0.20), (Low, 0.8), (Basic, 0)\}$$

II.2.3.3 Pilot's working experience (TP-WEx)

According to the given pilots' information, a membership function model can be constructed based on the number of years served as a pilot, as shown in Figure (II.2).

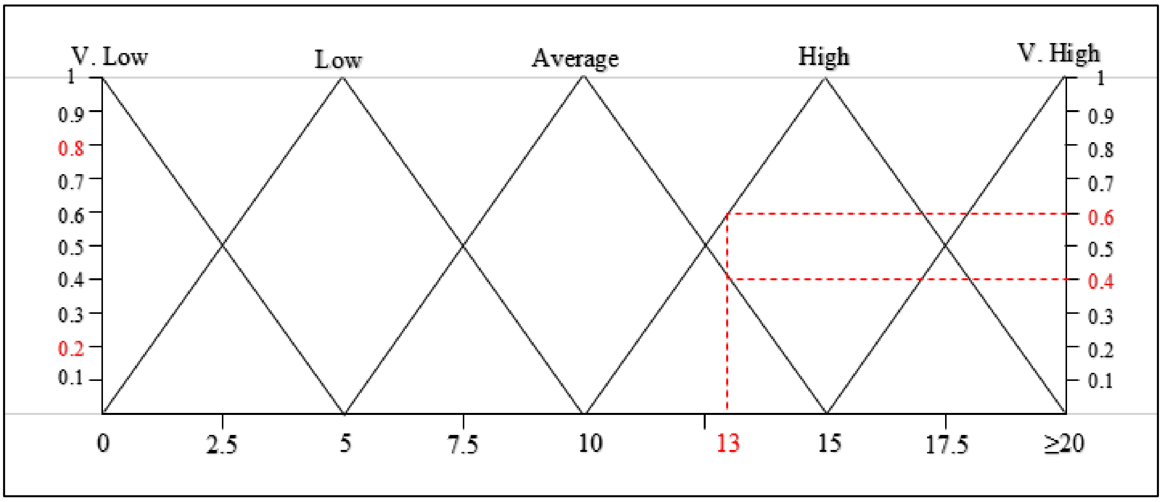

Figure II.2. The membership function for Pilot 2's working experience (TP-WEx)

The horizontal axis represents the quantitative number, while the vertical axis represents the belief degrees. When a given quantitative number is found in the range of $h_{n+1,i}$(with a grade H_{n+1}) and $h_{n,i}$(with a grade H_n), the belief degree can be calculated using the following formulas:

$$\beta_{n,i} = \frac{h_{n+1,i} - h_i}{h_{n+1,i} - h_{n,i}}, \text{ if } h_{n,i} < h_i < h_{n+1,i}$$

$$\beta_{n+1,i} = 1 - \beta_{n,i}$$

Where, $\beta_{n,i}$ is the degree of belief of the given quantitative number with the grade H_{n+1}. Based on the given information from Pilot 2, the degree of belief for Pilot's 2 TP-WEx can be calculated as follows:

1- H_{n+1} is the 'High' grade.

2- H_n is the 'Average' grade.

3- h_i= 13, $h_{n,i}$= 10, and $h_{n+1,i}$= 15.

4- $\beta_{n,i}$ = (15-13)/(15-10) = 0.4 with the 'Average' grade, and $\beta_{n+1,i}$ = 1-0.4 = 0.6 with the 'High' grade.

Therefore, the assessment of Pilot 2's TP-WExs is as follows:

$$\widetilde{WEx}_{p2} = \{(V.High, 0), (High, 0.6), (Average, 0.4), (Low, 0), (V.Low, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.12) for mapping pilots' WEx to its associated criterion, TP, in order to assess pilot reliability based on WEx.

Table II.12 Fuzzy rule base belief structure for TP-WEx

Working Experience (WEx) to Technical Proficiency (TP)	R^1: if WEx assessed 'Very High', then 100% 'V. Good' R^2: if WEx assessed 'High', then 80% 'Good' and 20% 'V. Good' R^3: if WEx assessed 'Average', then 80% 'Average' and 20% 'Good' R^4: if WEx assessed 'Low', then 90% 'Low' and 10% 'Average' R^5: if WEx assessed 'V. Low', then 100% 'Basic'

The fuzzy outputs from mapping WEx to TP, conducted based on given information for Pilot 2 and subject to fuzzy rules on Table II.12, are as follows:

Based on R^2 and R^3 the result can transform into 0.12 V. Good ($O^1 = 0.6 \times 0.2$), 0.56 Good ($O^2 = (0.6 \times 0.8) + (0.4 \times 0.2)$), and 0.32 Average ($O^3 = 0.4 \times 0.8$), respectively. Therefore, the WEx for Pilot 2 is assessed as follows:

$$TP - WEx_{p2} = \{(V.Good, 0.12), (Good, 0.56), (Average, 0.32), (Low, 0), (Basic, 0)\}$$

II.2.3.4 Pilot’s age

Due to the difficulty of how to assign a degree of belief to a pilot’s age, a range of assessments were proposed. Based on the experts’ opinions, that the membership function can be utilised in order to transform the grade for given quantitative data into a qualitative degree of beliefs, with reference to a study conducted by Riahi et al. (2012), the following rules were used:

1- If the pilot is 60 years old, he is considered ‘Very old’.
2- If the pilot is 50 years old, he is considered ‘Old’.
3- If the pilot is 40 years old, he is considered ‘Mid-Aged’.
4- If the pilot is 30 years old, he is considered ‘Young’.
5- If the pilot is 20 years old, he is considered ‘Very Young’.

Based on the information from each pilot, the membership function on Figure (II.3) represents the assessment F&S-OA of Pilot 2.

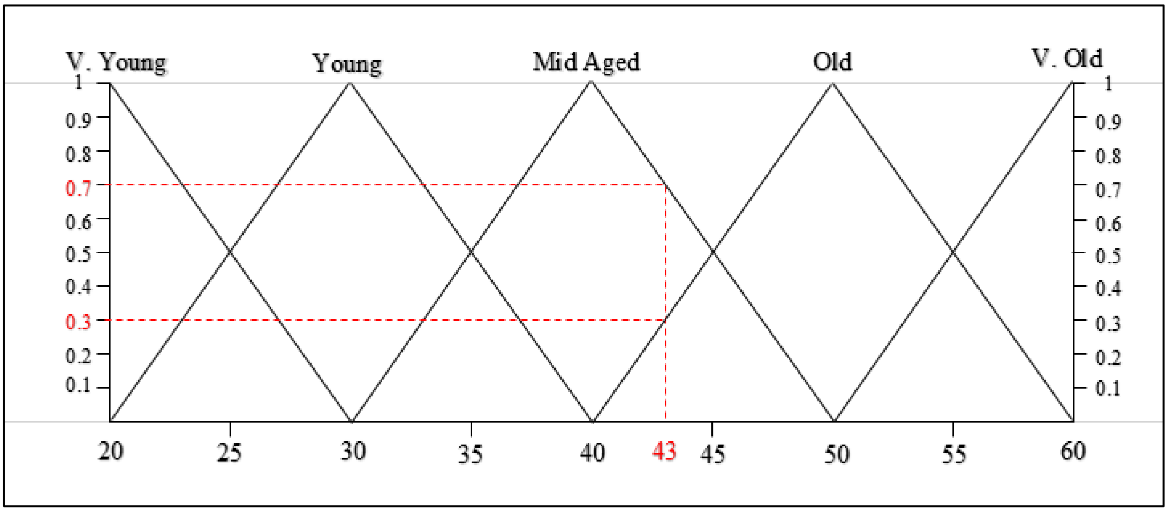

Figure II.3. The membership function for Pilot 2's age (F&S-OA)

The horizontal axis represents the quantitative number, while the vertical axis represents the belief degrees. When a given quantitative number is found in the range of $h_{n+1,i}$(with a grade H_{n+1}) and $h_{n,i}$(with a grade H_n), the belief degree can be calculated using the following formulas:

$$\beta_{n,i} = \frac{h_{n+1,i}-h_i}{h_{n+1,i}-h_{n,i}} \text{ , if } h_{n,i} < h_i < h_{n+1,i}$$

$$\beta_{n+1,i} = 1 - \beta_{n,i}$$

Where, $\beta_{n,i}$ is the degree of belief of the given quantitative number with the grade H_{n+1}. Based on the given information from Pilot 2, the degree of belief for Pilot 2's F&S-OA can be calculated as follows:

1- H_{n+1} is the ‘Old’ grade.

2- H_n is the ‘Mid Aged’ grade.

3- h_i= 43, $h_{n,i}$= 40, and $h_{n+1,i}$= 45.

4- $\beta_{n,i}$ = (45-43)/(45-40) = 0.7 with the ‘Mid Aged’ grade, and $\beta_{n+1,i}$ = 1-0.7 = 0.3 with the ‘Old’ grade.

Therefore, the assessment of Pilot 2's F&S-OA based on their information is as follows:

$$\widetilde{OA}_{\mathrm{p2}} = \{(Very\ Young, 0), (Young, 0), (Mid\ Aged, 0.7), (Old, 0.3), (Very\ Old, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.13) for mapping pilots’ OA to its associated criterion, F&S, in order to assess pilot reliability based on OA.

Table II.13 Fuzzy rule base belief structure for F&S-OA

Operator Age (OA) to Fitness & Strength (F&S)	R^1: if OA assessed ‘Very Young’, then 100% ‘Fit’ R^2: if OA assessed ‘Young’, then 80% ‘Good’ and 20% ‘Fit’ R^3: if OA assessed ‘Mid Aged’, then 90% ‘Moderate’ and 10% ‘Bad’ R^4: if OA assessed ‘Old’, then 80% ‘Bad’ and 20% ‘Unfit’ R^5: if OA assessed ‘Very Old’, then 100% ‘Unfit’

The fuzzy outputs from mapping OA to F&S, , conducted based on given information for Pilot 2 and subject to fuzzy rules on Table II.13, are as follows:

Based on $R^3$and R^4, the result can transform into 0.63 Moderate ($O^3 = 0.7 \times 0.9$), 0.31 Bad ($O^4 = (0.7 \times 0.1) + (0.3 \times 0.8)$), and 0.06 Unfit ($O^5 = 0.3 \times 0.2$), respectively. Therefore, the OA for Pilot 2 is assessed as follows:

$$F\&S - OA_{p2} = \{(Fit, 0), (Good, 0), (Moderate, 0.63), (Bad, 0.31), (Unfit, 0.06)\}$$

II.2.3.5 Mapping main criteria to goal

Following the aggregation process of all sub-criteria to their associated criterion, the main criterion can be further mapped similarly as above. Accordingly, the aggregated main criterion for Pilot 2 is as follows:

$$\widetilde{TP}_{\mathrm{p2}} = \{(V.Good, 0.09), (Good, 0.43), (Average, 0.33), (Low, 0.14), (Basic, 0)\}$$

$$\widetilde{PF}_{\mathrm{p2}} = \{(Neutral, 0.01), (S.Fatigued, 0.06), (Moderate, 0.28), (Fatigued, 0.36), (V.Bad, 0.29)\}$$

$$\widetilde{NTS}_{\mathrm{p2}} = \{(V.Good, 0.09), (Good, 0.42), (Moderate, 0.45), (Bad, 0.04), (V.Bad, 0)\}$$

$$\widetilde{F\&S}_{\mathrm{p2}} = \{(Fit, 0), (Good, 0.70), (Moderate, 0.28), (Bad, 0.03), (Unfit, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.14) for mapping Pilot 2 main criteria (TP, PF, NTS, and F&S) to the main goal, Pilot Reliability (PR).

Table II.14 Fuzzy rule base belief structure for Main criteria to PR

Technical Proficiency (TP) to Main Goal (PR)	R^1: if TP assessed ‘V. Good’, then 100% ‘Very High’ R^2: if TP assessed ‘Good’, then 80% ‘High’ and 20% ‘Very High’ R^3: if TP assessed ‘Average’, then 80% ‘Moderate’ and 20% ‘High’ R^4: if TP assessed ‘Low’, then 80% ‘Low’ and 20% ‘Very Low’ R^5: if TP assessed ‘Basic’, then 100% ‘Very Low’
Personal Fatigue (PF) to Main Goal (PR)	R^1: if TP assessed ‘Neutral, then 100% ‘Very High’ R^2: if TP assessed ‘S. Fatigued’, then 80% ‘High’ and 20% ‘Very High’ R^3: if TP assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘High’ R^4: if TP assessed ‘Fatigued’, then 80% ‘Low’ and 20% ‘Very Low’ R^5: if TP assessed ‘Very Bad’, then 100% ‘Very Low’
Non-Technical Skills (NTS) to Main Goal (PR)	R^1: if TP assessed ‘V. Good’, then 100% ‘Very High’ R^2: if TP assessed ‘Good’, then 80% ‘High’ and 20% ‘Very High’ R^3: if TP assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘High’ R^4: if TP assessed ‘Bad’, then 80% ‘Low’ and 20% ‘Very Low’ R^5: if TP assessed ‘V. Bad’, then 100% ‘Very Low’
Fitness & Strength (F&S) to Main Goal (PR)	R^1: if TP assessed ‘Fit’, then 100% ‘Very High’ R^2: if TP assessed ‘Good’, then 80% ‘High’ and 20% ‘V. High’ R^3: if TP assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘High’ R^4: if TP assessed ‘Bad’, then 80% ‘Low’ and 20% ‘Very Low’ R^5: if TP assessed ‘Unfit’, then 100% ‘Very Low’

Accordingly, the results obtained from the mapping process for Pilot 2 are as follows:

$$PRTP_{p2} = \{(V.High, 0.18), (High, 0.38), (Moderate, 0.30), (Low, 0.11), (V.Low, 0.03)\}$$

$$PRPF_{p2} = \{(V.High, 0.02), (High, 0.08), (Moderate, 0.26), (Low, 0.29), (V.Low, 0.36)\}$$

$$PRNTS_{p2} = \{(V.High, 0.18), (High, 0.38), (Moderate, 0.40), (Low, 0.03), (V.Low, 0.01)\}$$

$$PRF\&S_{p2} = \{(V.High, 0.14), (High, 0.58), (Moderate, 0.25), (Low, 0.02), (V.Low, 0.01)\}$$

II.2.4 Fuzzy set aggregation process

This section follows the same process as described on section (II.1.1-II.1.4). the result are presented as follows:

Table II.15. Aggregation of Technical Proficiency (TP) sub-criteria

Fuzzy output		Weight	Linguistic terms				
			V. Good	Good	Average	Low	Basic
Pilot 2	$\widetilde{TP}_{QPL}$	0.089	0.04	0.32	0.64	0	0
	$\widetilde{TP}_{ST}$	0.289	0	0	0.20	0.80	0
	$\widetilde{TP}_{WEx}$	0.622	0.12	0.56	0.32	0	0
Aggregation result			0.02	0.10	0.09	0.43	0.33

Table II.16. Aggregation of Personal Fatigue (PF) sub-criteria

Fuzzy output		Weight	Linguistic terms				
			Neutral	S. Fatigued	Moderate	Fatigued	V. Bad
Pilot 2	$\widetilde{PF}_{WH}$	0.210	0.06	0.38	0.56	0	0
	$\widetilde{PF}_{WS}$	0.366	0	0	0	0.32	0.68
	$\widetilde{PF}_{WEnv}$	0.424	0	0	0.40	0.50	0.10
Aggregation result			0.01	0.29	0.01	0.06	0.28

Table II.17. Aggregation of Non-Technical Skills (NTS) sub-criteria

Fuzzy output		Weight	Linguistic terms				
			V. Good	Good	Moderate	Bad	V. Bad
Pilot 2	$\widetilde{NTS}_{DM}$	0.075	0.04	0.16	0.72	0.08	0
	$\widetilde{NTS}_{SA}$	0.155	0.12	0.48	0.36	0.04	0
	$\widetilde{NTS}_{CS}$	0.234	0.06	0.24	0.63	0.07	0
	$\widetilde{NTS}_{T\&L}$	0.536	0.12	0.48	0.36	0.04	0
Aggregation result			0.05	0.19	0.09	0.42	0.45

Table II.18 Aggregation of Fitness & Strength (F&S) sub-criteria

Fuzzy output		Weight	Linguistic terms				
			Fit	Good	Moderate	Bad	Unfit
Pilot 2	$\widetilde{F\&S}_{OA}$	0.049	0	0	0.63	0.31	0.06
	$\widetilde{F\&S}_{HI}$	0.558	0	0.72	0.26	0.02	0
	$\widetilde{F\&S}_{BS}$	0.393	0	0.63	0.34	0.03	0
Aggregation result			0.82	0.15	0	0.70	0.28

Table II.19 Aggregation of pilot reliability (PR) main criterion

Fuzzy output		Weight	Linguistic terms				
			V. High	High	Moderate	Low	V. Low
Pilot 2	PR_{TP}	0.045	0.18	0.38	0.30	0.11	0.03
	PR_{PF}	0.186	0.02	0.08	0.26	0.29	0.36
	PR_{NTS}	0.606	0.18	0.38	0.40	0.03	0.01
	$PR_{F\&S}$	0.163	0.14	0.58	0.25	0.02	0.01
Aggregation result			0.15	0.38	0.37	0.06	0.04

II.2.5 Obtaining a pilot's 2 reliability using utility techniques

The result obtained from the aggregation of the 4 main criteria for each pilot, as shown on previous section, shows this is not a straightforward way to obtain a crisp reliability value for the assessed pilot. The aggregation process for Pilot 2's reliability is identified as follows:

$\widetilde{PR}$ = {(Very High, 0.15), (High, 0.38), (Moderate, 0.37), (Low, 0.06), (Very Low, 0.04)}

The fuzzy terms used to express the goal use five linguistic variables, where the highest preference term used is (Very High) while the lowest linguistic preference used is (Very Low). The utility value for assessing the reliability of a marine pilot can be identified as 0.6298, using equations (6.16-6.21), as presented in Table (II.20).

Table II.20 The reliability value for Pilot 2

H_n	Very High	High	Moderate	Low	Very Low
V_n	5	4	3	2	1
$u(H_n)$	$\frac{5-1}{5-1}=1$	$\frac{4-1}{5-1}=0.75$	$\frac{3-1}{5-1}=0.5$	$\frac{2-1}{5-1}=0.25$	$\frac{1-1}{5-1}=0$
β_n	0.15	0.37	0.37	0.06	0.04
$\sum_{n=1}^{5}\beta_n$	= 0.15+ 0.37+ 0.37+ 0.06+ 0.04= 1 $\longrightarrow \beta_H = 0$				
$\beta_n u(H_n)$	0.15	0.281	0.187	0.015	0
The reliability value for Pilot 2 = $\sum_{n=1}^{5}\beta_n u(H_n)$= 0.6298					

II.2.6 Sensitivity analysis

Table II.21 Decrement of lower preference value for technical proficiency (TP) sub-criteria

	Decrement	Linguistic terms				
		V. Good	Good	Average	Low	Basic
$\widetilde{TP}_{QPL}$	Main	0.04	0.32	0.64	0	0
	0.1	0.14	0.32	0.54	0	0
	0.2	0.24	0.32	0.44	0	0
	0.3	0.34	0.32	0.34	0	0
$\widetilde{TP}_{ST}$	Main	0	0	0.2	0.8	0
	0.1	0.1	0	0.2	0.7	0
	0.2	0.2	0	0.2	0.6	0
	0.3	0.3	0	0.2	0.5	0
$\widetilde{TP}_{WEx}$	Main	0.12	0.56	0.32	0	0
	0.1	0.22	0.56	0.22	0	0
	0.2	0.32	0.56	0.12	0	0
	0.3	0.42	0.56	0.02	0	0

Table II.22 Decrement of lower preference value for personal fatigue (PF) sub-criteria

	Decrement	Linguistic terms				
		Neutral	S. Fatigues	Moderate	Fatigued	V. Bad
$\widetilde{PF}_{WH}$	Main	0.06	0.38	0.56	0	0
	0.1	0.16	0.38	0.46	0	0
	0.2	0.26	0.38	0.36	0	0
	0.3	0.36	0.38	0.26	0	0
$\widetilde{PF}_{WS}$	Main	0	0	0	0.32	0.68
	0.1	0.1	0	0	0.32	0.58
	0.2	0.2	0	0	0.32	0.48
	0.3	0.3	0	0	0.32	0.38
$\widetilde{PF}_{WEnv}$	Main	0	0	0.4	0.5	0.1
	0.1	0.1	0	0.4	0.5	0
	0.2	0.2	0	0.4	0.4	0
	0.3	0.3	0	0.4	0.3	0

Table II.23 Decrement of lower preference value for non-technical skills (NTS) sub-criteria

Decrement		Linguistic terms				
		V. Good	Good	Moderate	Bad	V. Bad
$\widetilde{NTS}_{DM}$	Main	0.04	0.16	0.72	0.08	0
	0.1	0.14	0.16	0.70	0	0
	0.2	0.24	0.16	0.60	0	0
	0.3	0.34	0.16	0.50	0	0
$\widetilde{NTS}_{SA}$	Main	0.12	0.48	0.36	0.04	0
	0.1	0.22	0.48	0.30	0	0
	0.2	0.32	0.48	0.20	0	0
	0.3	0.42	0.48	0.10	0	0
$\widetilde{NTS}_{CS}$	Main	0.06	0.24	0.63	0.07	0
	0.1	0.16	0.24	0.60	0	0
	0.2	0.26	0.24	0.50	0	0
	0.3	0.36	0.24	0.40	0	0
$\widetilde{NTS}_{T\&L}$	Main	0.12	0.48	0.36	0.04	0
	0.1	0.22	0.48	0.30	0	0
	0.2	0.32	0.48	0.20	0	0
	0.3	0.42	0.48	0.10	0	0

Table II.24 Decrement of lower preference value for fitness & strength (F&S) sub-criteria

Decrement		Linguistic terms				
		Fit	Good	Moderate	Bad	Unfit
$\widetilde{F\&S}_{OA}$	Main	0	0	0.63	0.31	0.06
	0.1	0.1	0	0.63	0.27	0
	0.2	0.2	0	0.63	0.17	0
	0.3	0.3	0	0.63	0.07	0
$\widetilde{F\&S}_{HI}$	Main	0	0.72	0.26	0.02	0
	0.1	0.1	0.72	0.18	0	0
	0.2	0.2	0.72	0.08	0	0
	0.3	0.3	0.70	0	0	0
$\widetilde{F\&S}_{BS}$	Main	0	0.63	0.34	0.03	0
	0.1	0.1	0.63	0.27	0	0
	0.2	0.2	0.63	0.17	0	0
	0.3	0.3	0.63	0.07	0	0

According to the above increment and decrement process, the utility value for the goals in accordance to these changes are presented on Table (II.25), and a graph is drawn on Figure II.4.

Table II.25 Alteration of the median of Pilot 2's reliability due to lowest preference decrement

Sub-criterion	**Alteration of the median reliability value of a pilot's duo to the following decrease in the degree of belief associated to the lowest preferences linguistic term of the median fuzzy set of each sub-criterion**			
	Main	**- 0.1**	**- 0.2**	**- 0.3**
QPL	0.6298	0.6299	0.6299	0.6300
ST	0.6298	0.6302	0.6306	0.6310
WEx	0.6298	0.6309	0.6320	0.6332
WH	0.6298	0.6308	0.6317	0.6327
WS	0.6298	0.6338	0.6379	0.6419
WEnv	0.6298	0.6354	0.6398	0.6443
DM	0.6298	0.6323	0.6342	0.6362
SA	0.6298	0.6348	0.6392	0.6437
CS	0.6298	0.6388	0.6459	0.6531
T&L	0.6298	0.6580	0.6824	0.7079
OA	0.6298	0.6300	0.6302	0.6303
HI	0.6298	0.6334	0.6370	0.6401
BS	0.6298	0.6318	0.6336	0.6355

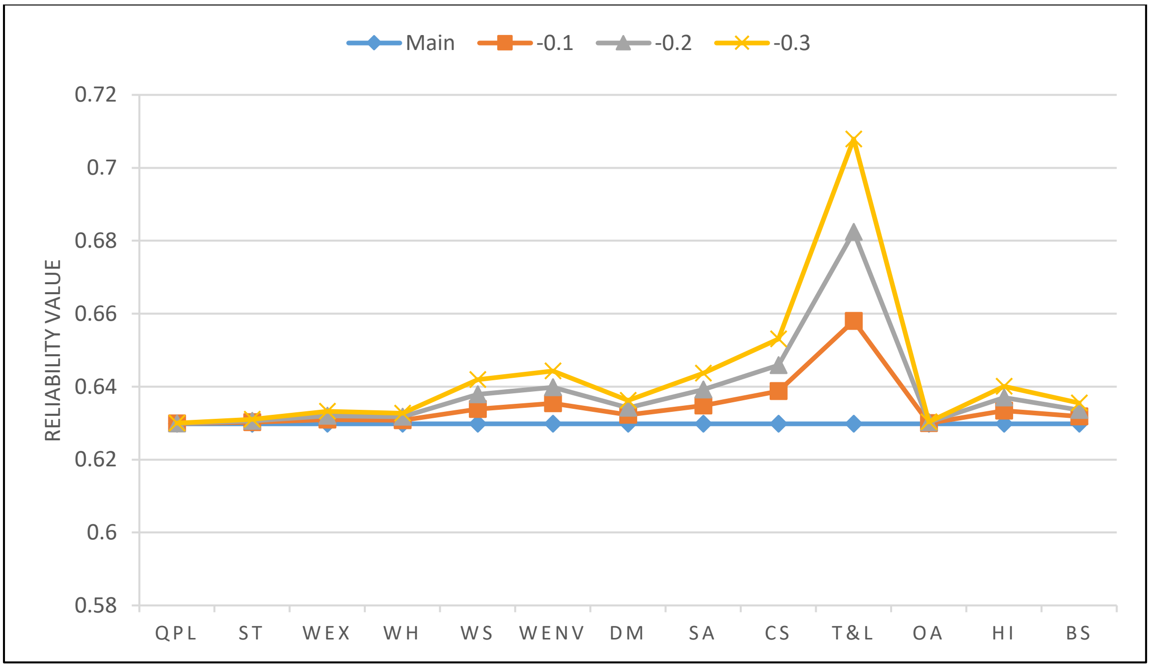

Figure II.4 Model sensitivity output for Pilot 2

II.3 Pilot 3

II.3.1 Mapping process for lower-level MPRI

II.3.1.1 Working hours (PF-WH)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 3's WH is as follows:

$$\widetilde{WH}_{p3} = \{(V.Good, 0), (Good, 0), (Moderate, 0), (Bad, 0.3), (V.Bad, 0.7)\}$$

The harbour masters at this port have agreed on the fuzzy rules in Table (II.26) for mapping pilots' WH to its associated criterion, PF, in order to assess pilot reliability based on WH.

Table II.26 Fuzzy rule base belief structure for PF-WH

Working Hours (WH) to Personal Fatigue (PF)	R^1: if WH assessed 'V. Good', then 100% 'Neutral' R^2: if WH assessed 'Good', then 80% 'S. Fatigued' and 20% 'Neutral' R^3: if WH assessed 'Moderate', then 80% 'Moderate' and 20% 'S. Fatigued' R^4: if WH assessed 'Bad', then 80% 'Fatigued' and 20% 'V. Bad' R^5: if WH assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping WH to PF can be conducted based on given information from Pilot 3 and subject to the fuzzy rules from Table II.26. They are as follows:

Based on R^4 and R^5, the result can transform into 0.24 Fatigued ($O^4 = 0.3 \times 0.8$), and 0.76 V. Bad ($O^5 = (0.3 \times 0.2) + (0.7 \times 1)$), respectively. Therefore, the WH for Pilot 2 is assessed as follows:

$$PF - WH_{p3}$$
$$= \{(Neutral, 0), (S.Fatigued, 0), (Moderate, 0), (Fatigued, 0.24), (V.Bad, 0.76)\}$$

II.3.1.2 Working stresses (PF-WS)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 3's WS is as follows:

$$\widetilde{WS}_{p3} = \{(V.Low, 0), (Low, 0), (Moderate, 0.4), (High, 0.6), (V.High, 0)\}$$

The harbour masters at this port have agreed on the fuzzy rules from Table (II.27) for mapping pilots' WS to its associated criterion, PF, in order to assess pilot reliability based on WS.

Table II.27 Fuzzy rule base belief structure for PF-WS

Working Stresses (WS) to Personal Fatigue (PF)	R^1: if WS assessed 'V. Low', then 100% 'Neutral' R^2: if WS assessed 'Low', then 90% 'S. Fatigued' and 10% 'Moderate' R^3: if WS assessed 'Moderate', then 80% 'Moderate' and 20% 'Fatigued' R^4: if WS assessed 'High', then 80% 'Fatigued' and 20% 'V. Bad' R^5: if WS assessed 'V. High', then 100% 'V. Bad'

The fuzzy outputs from mapping WS to PF, conducted based on given information for Pilot 3 and subject to fuzzy rules from Table II.27, are as follow:

Based on $R^3$and R^4, the result can transform into 0.32 Moderate ($O^3 = 0.4 \times 0.8$), 0.56 Fatigued ($O^4 = (0.4 \times 0.2) + (0.6 \times 0.8)$), and 0.12 V. Bad ($O^5 = 0.6 \times 0.2$), respectively. Therefore, the WS for Pilot 3 is assessed as follows:

$$PF - WS_{p3}$$
$$= \{(Neutral, 0), (S.Fatigued, 0), (Moderate, 0.32), (Fatigued, 0.56), (V.Bad, 0.12)\}$$

II.3.1.3 Working environment (PF-WEnv)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 3's WEnv is as follows:

$$\widetilde{WEnv}_{p3} = \{(V.Good, 0), (Good, 0), (Moderate, 0.3), (Bad, 0.7), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules of Table (II.28) for mapping pilots' WEnv to its associated criterion, PF, in order to assess pilot reliability based on WS.

Table II.28 Fuzzy rule base belief structure for PF-WEnv

Working Environment (WEnv) to Personal Fatigue (PF)	R^1: if WEnv assessed ‘V. Good’, then 100% ‘Neutral’
	R^2: if WEnv assessed ‘Good’, then 80% ‘S. Fatigued’ and 20% ‘Moderate’
	R^3: if WEnv assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘Fatigued’
	R^4: if WEnv assessed ‘Bad’, then 80% ‘Fatigued’ and 20% ‘V. Bad’
	R^5: if WEnv assessed ‘V. Bad’, then 100% ‘V. Bad’

The fuzzy outputs from mapping WEnv to PF, conducted based on given information from Pilot 3 and subject to fuzzy rules from Table II.28, are as follow:

Based on $R^3$and R^4, the result can transform into 0.24 Moderate ($O^3 = 0.3 \times 0.8$), 0.62 Fatigued ($O^4 = (0.3 \times 0.2) + (0.7 \times 0.8)$), and 0.14 V. Bad ($O^5 = 0.7 \times 0.2$), respectively. Therefore, the WEnv for Pilot 3 is assessed as follows:

$$PF - WEnv_{p3}$$

$$= \{(Neutral, 0), (S.Fatigued, 0), (Moderate, 0.24), (Fatifued, 0.62), (V.Bad, 0.14)\}$$

II.3.1.4 Decision-making (NTS-DM)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 3’s DM is as follows:

$$\widetilde{DM}_{p3} = \{(V.Good, 0.4), (Good, 0.6), (Average, 0), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules from Table (II.29) for mapping pilots’ DM to its associated criterion, NTS, in order to assess pilot reliability based on DM.

Table II.29 Fuzzy rule base belief structure for NTS-DM

Decision Making (DM) to Non-technical Skills (NTS)	R^1: if DM assessed ‘V. Good’, then 100% ‘V. Good’
	R^2: if DM assessed ‘Good’, then 80% ‘Skilful’ and 20% ‘V. Good’
	R^3: if DM assessed ‘Average’, then 90% ‘Moderate’ and 10% ‘Bad’
	R^4: if DM assessed ‘Bad’, then 80% ‘Bad’ and 20% ‘V. Bad’
	R^5: if DM assessed ‘V. Bad’, then 100% ‘V. Bad’

The fuzzy outputs from mapping DM to NTS, conducted based on given information from Pilot 3 and subject to fuzzy rules from Table II.29, are as follows:

Based on $R^1$and R^2, the result can transform into 0.52 V. Good ($O^1 = (0.4 \times 1) + (0.6 \times 0.2)$), and 0.48 Good ($O^2 = 0.6 \times 0.8$), respectively. Therefore, the DM for Pilot 3 is assessed as follows:

$$NTS - DM_{p3} = \{(V.Good, 0.52), (Good, 0.48), (Moderate, 0), (Bad, 0), (V.Bad, 0)\}$$

II.3.1.5 Situation awareness (NTS-SA)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 3's SA is as follows:

$$\widetilde{SA}_{p3} = \{(V.Good, 0.2), (Good, 0.8), (Average, 0), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.30) for mapping pilots' SA to its associated criterion, NTS, in order to assess pilot reliability based on SA.

Table II.30 Fuzzy rule base belief structure for NTS-SA

Situation Awareness (SA) to Non-technical Skills (NTS)	R^1: if SA assessed 'V. Good', then 100% 'V. Good' R^2: if SA assessed 'Good', then 80% 'Skilful' and 20% 'V .Good' R^3: if SA assessed 'Average', then 90% 'Moderate' and 10% 'Bad' R^4: if SA assessed 'Bad', then 80% 'Bad' and 20% 'V. Bad' R^5: if SA assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping SA to NTS, conducted based on given information for Pilot 3 and subject to fuzzy rules from Table II.30, are as follows:

Based on $R^1$and R^2, the result can transform into 0.36 V. Good($O^1 = (0.2 \times 1) + (0.8 \times 0.2)$), and 0.64 Good ($O^2 = 0.8 \times 0.8$), respectively. Therefore, the SA for Pilot 3 is assessed as follows:

$$NTS - SA_{p3} = \{(V.Good, 0.36), (Good, 0.64), (Moderate, 0), (Bad, 0), (V.Bad, 0)\}.$$

II.3.1.6 Communication skills (NTS-CS)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 3's CS is as follows:

$$\widetilde{CS}_{p3} = \{(V.Good, 0), (Good, 0.5), (Average, 0.5), (Bad, 0), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.31) for mapping pilots' CS to its associated criterion, NTS, in order to assess pilot reliability based on CS.

Table II.31 Fuzzy rule base belief structure for NTS- CS

Communication Skills (CS) to Non-technical Skills (NTS)	R^1: if CS assessed 'V. Good', then 100% 'V. Good' R^2: if CS assessed 'Good', then 80% 'Skilful' and 20% 'V. Good' R^3: if CS assessed 'Average', then 90% 'Moderate' and 10% 'Bad' R^4: if CS assessed 'Bad', then 80% 'Bad' and 20% 'V. Bad' R^5: if CS assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping CS to NTS, conducted based on given information for Pilot 3 and subject to fuzzy rules on table II.31, are as follows:

Based on $R^2$and R^3, the result can transform into 0.10 V. Good ($O^1 = 0.5 \times 0.2$), 0.40 Good ($O^2 = 0.5 \times 0.8$), 0.45 Moderate ($O^3 = 0.5 \times 0.9$), and 0.05 Bad ($O^4 = 0.5 \times 0.1$), respectively. Therefore, the CS for Pilot 3 is assessed as follows:

$$NTS - \mathrm{CS}_{p3} = \{(V.Good, 0.10), (Good, 0.40), (Moderate, 0.45), (Bad, 0.05), (V.Bad, 0)\}$$

II.3.1.7 Teamwork and leadership (NTS-T&L)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 3's T&L is as follows:

$$\widetilde{T\&L}_{p3} = \{(V.Good, 0), (Good, 0), (Average, 0.4), (Bad, 0.6), (V.Bad, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.32) for mapping pilots' T&L to its associated criterion, NTS, in order to assess pilot reliability based on T&L.

Table II.32 Fuzzy rule base belief structure for NTS-T&L

Teamwork and Leadership (T&L) to Non-technical Skills (NTS)	R^1: if T&L assessed 'V. Good', then 100% 'V. Good' R^2: if T&L assessed 'Good', then 80% 'Skilful' and 20% 'V. Good' R^3: if T&L assessed 'Average', then 90% 'Moderate' and 10% 'Bad' R^4: if T&L assessed 'Bad', then 80% 'Bad' and 20% 'V. Bad' R^5: if T&L assessed 'V. Bad', then 100% 'V. Bad'

The fuzzy outputs from mapping T&L to NTS, conducted based on given information for Pilot 3 and subject to fuzzy rules on Table II.32, are as follows:

Based on $R^3$and R^4, the result can transform into 0.36 Moderate ($O^3 = 0.4 \times 0.9$), 0.52 Bad ($O^4 = (0.4 \times 0.1) + (0.6 \times 0.8)$), and 0.12 V. Bad($O^5 = 0.6 \times 0.2$), respectively. Therefore, the T&L for Pilot 3 is assessed as follows:

$$NTS - T\&L_{p3} = \{(V.Good, 0), (Good, 0), (Moderate, 0.36), (Bad, 0.52), (V.Bad, 0.12)\}$$

II.3.1.8 Health Issues (F&S-HI)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 3's HI is as follows:

$$\widetilde{HI}_{p3} = \{(Healthy, 0), (Good, 0), (Moderate, 1), (Bad, 0), (Severe, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.33) for mapping pilots' HI to its associated criterion, F&S, in order to assess pilot reliability based on HI.

Table II.33 Fuzzy rule base belief structure for F&S-HI

Health Issue (HI) to Fitness and Strength (F&S)	R^1: if HI assessed 'Healthy', then 100% 'Fit' R^2: if HI assessed 'Good', then 90% 'Good' and 10% 'Moderate' R^3: if HI assessed 'Moderate', then 90% 'Moderate' and 10% 'Bad' R^4: if HI assessed 'Bad', then 80% 'Bad' and 20% 'Unfit' R^5: if HI assessed 'Severe', then 100% 'Unfit'

The fuzzy outputs from mapping 'HI' to F&S, conducted based on given information for Pilot 3 and subject to fuzzy rules on Table II.33, are as follows:

Based on R^3, the result can transform into 0.90 Moderate ($O^3 = 1 \times 0.9$), and 0.10 Bad ($O^4 = 1 \times 0.1$), respectively. Therefore, the HI for Pilot 3 is assessed as follows:

$$F\&S - HI_{p3} = \{(Fit, 0), (Good, 0), (Moderate, 0.90), (Bad, 0.10), (Unfit, 0)\}$$

II.3.1.9 Body strength (F&S-BS)

Based on the information given in Table 6.1, the fuzzy evaluation for the marine pilot 3's BS is as follows:

$$\widetilde{BS}_{p3} = \{(Fit, 0), (Good, 0), (Moderate, 0.8), (Weake, 0.2), (V.Weake, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.34) for mapping pilots' BS to its associated criterion, F&S, in order to assess pilot reliability based on BS.

Table II.34 Fuzzy rule base belief structure for F&S-BS

Body Strength (BS) to Fitness and Strength (F&S)	R^1: if BS assessed 'Fit', then 100% 'Fit' R^2: if BS assessed 'Good', then 90% 'Good' and 10% 'Moderate' R^3: if BS assessed 'Moderate', then 90% 'Moderate' and 10% 'Bad' R^4: if BS assessed 'Weak', then 80% 'Bad' and 20% 'Unfit' R^5: if BS assessed 'V. Weak', then 100% 'Unfit'

The fuzzy outputs from mapping BS to F&S, conducted based on given information for Pilot 3 and subject to fuzzy rules on Table II.34, are as follows:

Based on $R^3$and R^4, the result can transform into 0.72 Moderate ($O^3 = 0.8 \times 0.9$), 0.24 Bad ($O^4 = (0.8 \times 0.1) + (0.2 \times 0.8)$), and 0.04 Unfit ($O^5 = 0.2 \times 0.2$), respectively. Therefore, the BS for Pilot 3 is assessed as follows:

$$F\&S - BS_{p3} = \{(Fit, 0), (Good, 0), (Moderate, 0.72), (Bad, 0.24), (Unfit, 0.04)\}$$

II.3.2 Transforming quantitative data into qualitative

II.3.2.1 Pilot's qualification and pilotage licensing (TP-QPL)

The harbour masters at this port have assigned the following marks of value to fuzzy rules to evaluate pilot reliability based on the pilot's QPL:

1- If the pilot holds an approved diploma or a BSc in nautical science and an approved pilot license from the port authority, he will be given 50 per cent. The pilot must satisfy 100 per cent of the port's minimum requirements.

2- If the pilot holds an approved diploma with an approved certificate of competency class 4 (COC IIII) as a 3rd officer, he will be given 60 per cent. Therefore, the pilot is evaluated as 20 per cent at minimum and 80 per cent at second minimum requirement.

3- If the pilot holds an approved diploma with an approved certificate of competency class 3 (COC III) as a 2nd officer or BSc with an approved (COC IIII) as a 3rd officer, then he will be given 70 per cent. Therefore, the pilot is evaluated as 80 per cent at second minimum requirement and 20 per cent on average, which represent the third requirement.

4- If the pilot holds an approved diploma with an approved certificate of competency class 2 (COC II) as a 1st officer or BSc with an approved (COC III) as a 2nd officer, then he will be given 80%. Therefore, the pilot is evaluated as 80 per cent average and 20 per cent second higher requirement.

5- If the pilot holds an approved diploma with an approved certificate of competency class 1 (COC I) as a master mariner or BSc with an approved (COC II) as a 1st officer, then he will be given 90%. Therefore, the pilot is evaluated as 80 per cent second required qualification and 20 per cent uppermost.

6- If the pilot holds an approved BSc with an approved (COC I) as a master mariner, then he will be given 100%. Therefore, the pilot is evaluated as 100 per cent the uppermost requirement.

According to the given pilots' information, with reference to the above rules, Pilot 3's TP-QPL is assessed based on his QPL as follows:

$$\widetilde{QPL}_{p3} = \{(Uppermost, 0), (Second\ Higher, 0), (Average, 0), (Second\ Min., 0), (V.Min., 1)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.35) for mapping pilots' QPL to its associated criterion, TP, in order to assess pilot reliability based on QPL.

Table II.35 Fuzzy rule base belief structure for TP-QPL

Qualification and pilotage licensing (QPL) to Technical Proficiency (TP)	R^1: if QPL assessed 'Uppermost', then 100% 'V. Good'
	R^2: if QPL assessed '2nd Higher', then 80% 'Good' and 20% 'V. Good'
	R^3: if QPL assessed 'Average', then 80% 'Average' and 20% 'Good'
	R^4: if QPL assessed '2nd Min.', then 90% 'Low' and 10% 'Average'
	R^5: if QPL assessed 'V. Min', then 100% 'Basic'

The fuzzy outputs from mapping QPL to TP, conducted based on given information for Pilot 3 and subject to fuzzy rules on Table II.35, are as follow:

Based on R^5, the result can transform into 1 Basic ($O^5 = 1 \times 1$),. Therefore, the QPL for Pilot 3 is assessed as follows:

$$TP - QPL_{p3} = \{(V.Good, 0), (Good, 0), (Average, 0), (Low, 0), (Basic, 1)\}$$

II.3.2.2 Pilot's special training (TP-ST)

Similar to the requirements of pilot qualifications required by the port authority, there are sets of minimum basic training courses that are also essential for a pilot to be endorsed. According to the port authority requirements, the following are compulsory basic training courses that a pilot must have when applying for a pilotage license:

1- Proficiency in Survival Craft (PSC);

2- Personal Survival Technique (PST);

3- Fire Prevention and Firefighting (FPF);

4- Elementary First Aid (EFA);

5- Advanced Fire Prevention and Firefighting (AFF).

The authority also recommends some extra training courses, but they are optional. These extra courses are:

1- Global Maritime Distress and Safety System (GMDSS) training;

2- Radar simulation training;

3- Advanced Pilot Training (APT) course;

4- Bridge Resource Management (BRM) training course;
5- Port State Control (PSC) training;
6- Ship-handling simulator.

According to the experts' opinions, having valid course certificates for more than nine courses makes one a 'well-trained' pilot. This information helps in developing the membership function used to evaluate pilots based on their ST. Accordingly, if the pilot holds one of these certificates, then 10 per cent will be given for each valid certificate; if the certificate is not valid, then 0 per cent is given. Based on the pilot's given information in the test case, the following are the training courses that Pilot 3 has:

1- Proficiency in survival craft (PSC) (Valid);
2- Personal survival technique (PST) (Valid);
3- Fire prevention and firefighting (FPFF) (Not Valid);
4- Elementary first aid (EFA) (Valid);
5- Advanced fire prevention and firefighting certificate (AFF) (Not Valid);
6- Ship-handling simulator certificate (Valid);
7- Global Maritime Distress and Safety System (GMDSS) certificate (Not Valid);
8- Advanced Pilot Training (APT) certificate (Valid);

Based on the pilot's stated valid training certificates, 50 per cent is given to Pilot 3. The membership function model constructed is shown in Figures (II.5).

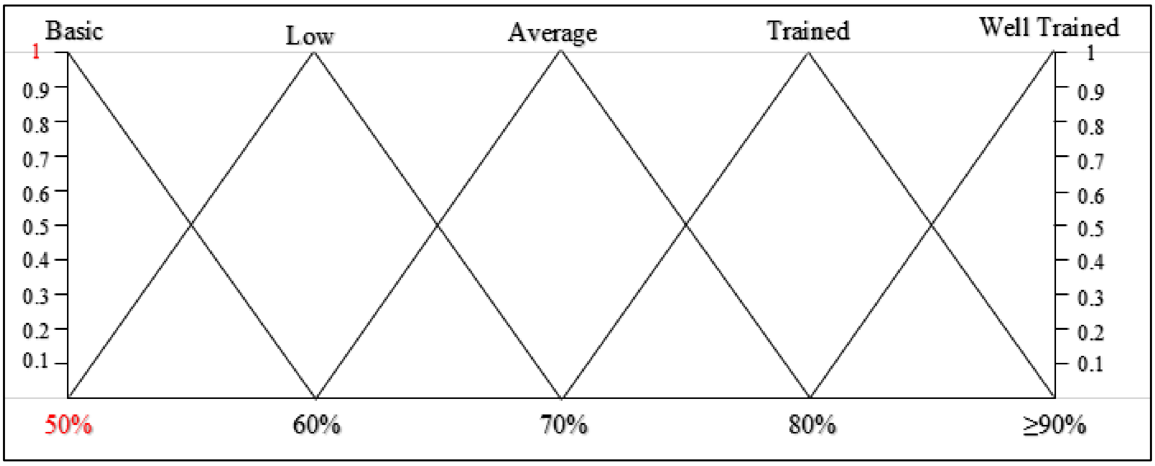

Figure II.5 The membership function for Pilot 3's special training (TP-ST)

The horizontal axis represents the quantitative number, while the vertical axis represents the belief degrees. When a given quantitative number is found not ranging between two different grades, then 100 per cent will be given. According to the given pilot's information, with reference to the above information, Pilot 3's TP-ST is assessed based on his ST as follows:

$$\widetilde{ST}_{\mathrm{p3}} = \{(Well\ Trained, 0), (Trained, 0), (Average, 0), (Low, 0), (Basic, 1)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.36) for mapping pilots' ST to its associated criterion, TP, in order to assess pilot reliability based on ST.

Table II.36 Fuzzy rule base belief structure for TP-ST

Special Training (ST) to Technical Proficiency (TP)	R^1: if ST assessed 'Well Trained', then 100% 'V. Good'
	R^2: if ST assessed 'Trained', then 80% 'Good' and 20% 'V. Good'
	R^3: if ST assessed 'Average', then 80% 'Average' and 20% 'Good'
	R^4: if ST assessed 'Low', then 80% 'Low' and 20% 'Average'
	R^5: if ST assessed 'Basic', then 100% 'Basic'

The fuzzy outputs from mapping ST to TP, conducted based on given information for Pilot 3 and subject to fuzzy rules on Table II.36, are as follows:

Based on R^5 the result can transform into 1 Basic ($O^5 = 1 \times 1$). Therefore, the ST for Pilot 3 is assessed as follows:

$$TP - ST_{p3} = \{(V.Good, 0), (Good, 0), (Average, 0), (Low, 0), (Basic, 1)\}$$

II.3.2.3 Pilot's working experience (TP-WEx)

According to the given pilots' information, a membership function model can be constructed based on the number of years served as a pilot, as shown in Figure (II.6).

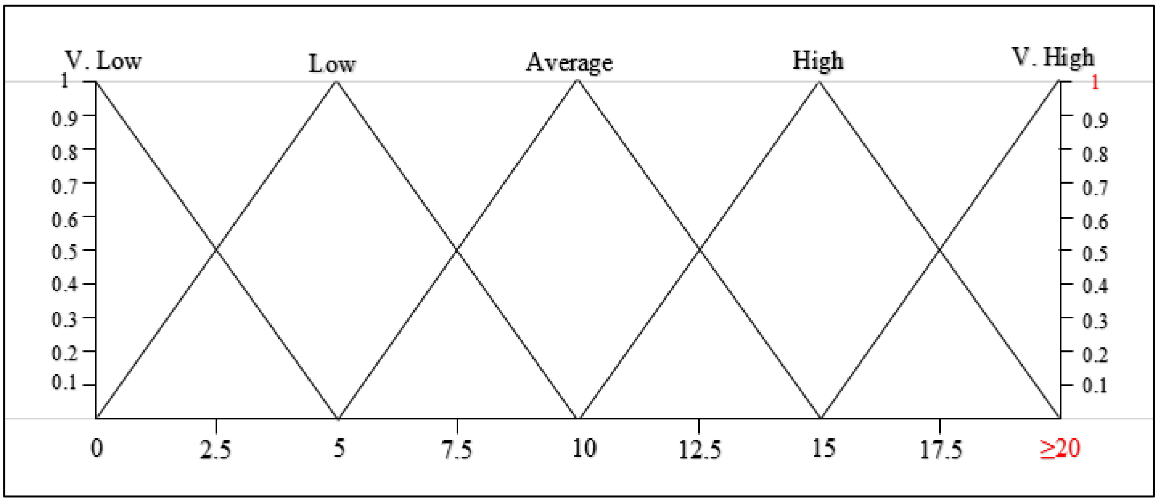

Figure II.6 The membership function for Pilot 3's working experience (TP-WEx)

Therefore, the assessment of Pilot 3's TP-WExs is as follows:

$$\widetilde{WEx}_{p3} = \{(V.High, 1), (High, 0), (Average, 0), (Low, 0), (V.Low, 0)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.37) for mapping pilots' WEx to its associated criterion, TP, in order to assess pilot reliability based on WEx.

Table II.37 Fuzzy rule base belief structure for TP-WEx

Working Experience (WEx) to Technical Proficiency (TP)	R^1: if WEx assessed 'Very High', then 100% 'V. Good' R^2: if WEx assessed 'High', then 80% 'Good' and 20% 'V. Good' R^3: if WEx assessed 'Average', then 80% 'Average' and 20% 'Good' R^4: if WEx assessed 'Low', then 90% 'Low' and 10% 'Average' R^5: if WEx assessed 'V. Low', then 100% 'Basic'

The fuzzy outputs from mapping WEx to TP, conducted based on given information for Pilot 3 and subject to fuzzy rules on Table II.37, are as follows:

Based on R^1result can transform into 1 V. Good ($O^1 = 1 \times 1$). Therefore, the WEx for Pilot 3 is assessed as follows:

$$TP - WEx_{p3} = \{(V.Good, 1), (Good, 0), (Average, 0), (Low, 0), (Basic, 0)\}$$

II.3.2.4 Pilot’s age

Due to the difficulty of how to assign a degree of belief to a pilot’s age, a range of assessments were proposed. Based on the experts’ opinions, that the membership function can be utilised in order to transform the grade for given quantitative data into a qualitative degree of beliefs, with reference to a study conducted by Riahi et al. (2012), the following rules were used:

1- If the pilot is 60 years old, he is considered ‘Very old’.

2- If the pilot is 50 years old, he is considered ‘Old’.

3- If the pilot is 40 years old, he is considered ‘Mid-Aged’.

4- If the pilot is 30 years old, he is considered ‘Young’.

5- If the pilot is 20 years old, he is considered ‘Very Young’.

Based on the information from each pilot, the membership function on Figure (II.7) represents the assessment F&S-OA of Pilot 3.

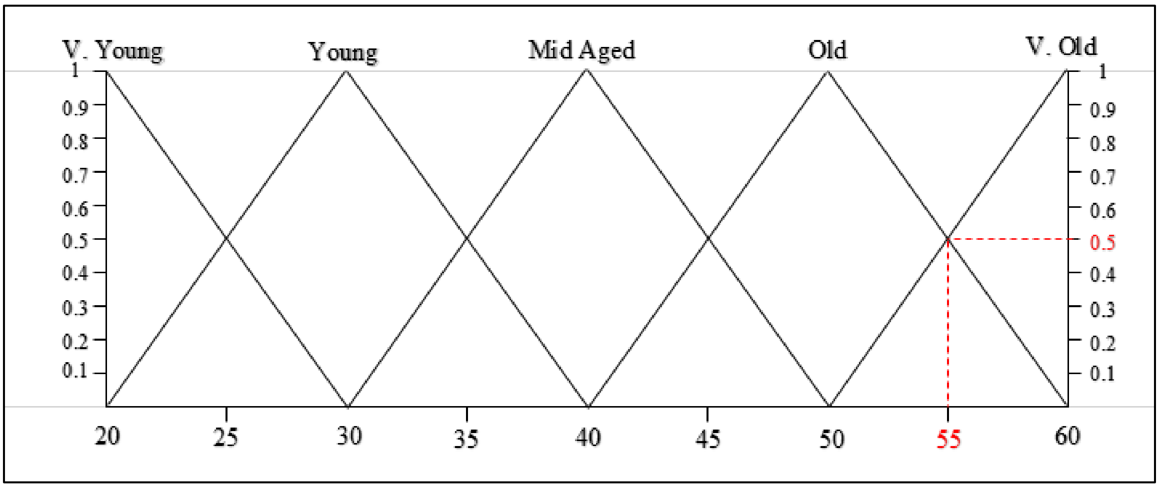

Figure II.7 The membership function for Pilot 3's age (F&S-OA)

The horizontal axis represents the quantitative number, while the vertical axis represents the belief degrees. When a given quantitative number is found in the range of $h_{n+1,i}$(with a grade H_{n+1}) and $h_{n,i}$(with a grade H_n), the belief degree can be calculated using the following formulas:

$\beta_{n,i} = \frac{h_{n+1,i}-h_i}{h_{n+1,i}-h_{n,i}}$, if $h_{n,i} < h_i < h_{n+1,i}$

$\beta_{n+1,i} = 1 - \beta_{n,i}$

Where, $\beta_{n,i}$ is the degree of belief of the given quantitative number with the grade H_{n+1}. Based on the given information from Pilot 3, the degree of belief for Pilot 3's F&S-OA can be calculated as follows:

1- H_{n+1} is the 'V. Old' grade.

2- H_n is the 'Old' grade.

3- h_i= 55, $h_{n,i}$= 50, and $h_{n+1,i}$= 60.

4- $\beta_{n,i}$ = (60-55)/(60-50) = 0.5 with the 'Old' grade, and $\beta_{n+1,i}$ = 1-0.5 = 0.5 with the 'V. Old' grade.

Therefore, the assessment of Pilot 3's F&S-OA based on their information is as follows:

$\widetilde{OA}_{\text{p3}} = \{(Very\ Young, 0), (Young, 0), (Mid\ Aged, 0), (Old, 0.5), (Very\ Old, 0.5)\}$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.38) for mapping pilots' OA to its associated criterion, F&S, in order to assess pilot reliability based on OA.

Table II.38 Fuzzy rule base belief structure for F&S-OA

Operator Age (OA) to Fitness & Strength (F&S)	R^1: if OA assessed 'Very Young', then 100% 'Fit' R^2: if OA assessed 'Young', then 80% 'Good' and 20% 'Fit' R^3: if OA assessed 'Mid Aged', then 90% 'Moderate' and 10% 'Bad' R^4: if OA assessed 'Old', then 80% 'Bad' and 20% 'Unfit' R^5: if OA assessed 'Very Old', then 100% 'Unfit'

The fuzzy outputs from mapping OA to F&S, , conducted based on given information for Pilot 3 and subject to fuzzy rules on Table II.38, are as follows:

Based on $R^4$and R^5 the result can transform into 0.4 Bad ($O^4 = 0.5 \times 0.8$), and 0.6 Unfit ($O^5 = (0.5 \times 0.2) + (0.5 \times 1)$), respectively. Therefore, the OA for Pilot 3 is assessed as follows:

$$F\&S - OA_{p3} = \{(Fit, 0), (Good, 0), (Moderate, 0), (Bad, 0.4), (Unfit, 0.6)\}$$

II.3.2.5 Mapping main criteria to goal

Following the aggregation process of all sub-criteria to their associated criterion, the main criterion can be further mapped similarly as above. Accordingly, the aggregated main criterion for Pilot 3 is as follows:

$$\widetilde{TP}_{\mathrm{p3}} = \{(V.Good, 0.75), (Good, 0), (Average, 0), (Low, 0), (\mathrm{Basic}, 0.25)\}$$

$$\widetilde{PF}_{\mathrm{p3}} = \{(Neutral, 0), (S.Fatigued, 0), (Moderate, 0.21), (Fatigued, 0.56), (V.Bad, 0.22)\}$$

$$\widetilde{NTS}_{\mathrm{p3}} = \{(V.Good, 0.08), (Good, 0.17), (Moderate, 0.34), (Bad, 0.34), (V.Bad, 0.08)\}$$

$$\widetilde{F\&S}_{\mathrm{p3}} = \{(Fit, 0), (Good, 0), (Moderate, 0.85), (Bad, 0.13), (Unfit, 0.02)\}$$

The harbour masters at this port have agreed to the fuzzy rules on Table (II.39) for mapping Pilot 3 main criteria (TP, PF, NTS, and F&S) to the main goal, Pilot Reliability (PR).

Table II.39 Fuzzy rule base belief structure for Main criteria to PR

Technical Proficiency (TP) to Main Goal (PR)	R^1: if TP assessed ‘V. Good’, then 100% ‘Very High’
	R^2: if TP assessed ‘Good’, then 80% ‘High’ and 20% ‘Very High’
	R^3: if TP assessed ‘Average’, then 80% ‘Moderate’ and 20% ‘High’
	R^4: if TP assessed ‘Low’, then 80% ‘Low’ and 20% ‘Very Low’
	R^5: if TP assessed ‘Basic’, then 100% ‘Very Low’
Personal Fatigue (PF) to Main Goal (PR)	R^1: if TP assessed ‘Neutral, then 100% ‘Very High’
	R^2: if TP assessed ‘S. Fatigued’, then 80% ‘High’ and 20% ‘Very High’
	R^3: if TP assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘High’
	R^4: if TP assessed ‘Fatigued’, then 80% ‘Low’ and 20% ‘Very Low’
	R^5: if TP assessed ‘Very Bad’, then 100% ‘Very Low’
Non-Technical Skills (NTS) to Main Goal (PR)	R^1: if TP assessed ‘V. Good’, then 100% ‘Very High’
	R^2: if TP assessed ‘Good’, then 80% ‘High’ and 20% ‘Very High’
	R^3: if TP assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘High’
	R^4: if TP assessed ‘Bad’, then 80% ‘Low’ and 20% ‘Very Low’
	R^5: if TP assessed ‘V. Bad’, then 100% ‘Very Low’
Fitness & Strength (F&S) to Main Goal (PR)	R^1: if TP assessed ‘Fit’, then 100% ‘Very High’
	R^2: if TP assessed ‘Good’, then 80% ‘High’ and 20% ‘V. High’
	R^3: if TP assessed ‘Moderate’, then 80% ‘Moderate’ and 20% ‘High’
	R^4: if TP assessed ‘Bad’, then 80% ‘Low’ and 20% ‘Very Low’
	R^5: if TP assessed ‘Unfit’, then 100% ‘Very Low’

$$PRTP_{p3} = \{(V.High, 0.75), (High, 0), (Moderate, 0), (Low, 0), (V.Low, 025)\}$$

$$PRPF_{p3} = \{(V.High, 0), (High, 0.02), (Moderate, 0.19), (Low, 0.45), (V.Low, 0.34)\}$$

$$PRNTS_{p3} = \{(V.High, 0.11), (High, 0.17), (Moderate, 0.30), (Low, 0.27), (V.Low, 0.14)\}$$

$$PRF\&S_{p3} = \{(V.High, 0), (High, 0.08), (Moderate, 0.76), (Low, 0.10), (V.Low, 0.05)\}$$

II.3.3 Fuzzy set aggregation process

This section follows the same process as described on section (II.1.1-II.1.4). The result are presented as follows:

Table II.40 Aggregation of Technical Proficiency (TP) sub-criteria

Fuzzy output		Weight	Linguistic terms				
			V. Good	Good	Average	Low	Basic
Pilot 3	$\widetilde{TP}_{QPL}$	0.089	0	0	0	0	1
	$\widetilde{TP}_{ST}$	0.289	0	0	0	0	1
	$\widetilde{TP}_{WEx}$	0.622	1	0	0	0	0
Aggregation result			0.75	0	0	0	0.25

Table II.41 Aggregation of Personal Fatigue (PF) sub-criteria

Fuzzy output		Weight	Linguistic terms				
			Neutral	S. Fatigued	Moderate	Fatigued	V. Bad
Pilot 3	$\widetilde{PF}_{WH}$	0.210	0	0	0	0.24	0.76
	$\widetilde{PF}_{WS}$	0.366	0	0	0.32	0.56	0.12
	$\widetilde{PF}_{WEnv}$	0.424	0	0	0.24	0.62	0.14
Aggregation result			0	0	0.21	0.56	0.22

Table II.42 Aggregation of Non-Technical Skills (NTS) sub-criteria

Fuzzy output		Weight	Linguistic terms				
			V. Good	Good	Moderate	Bad	V. Bad
Pilot 3	$\widetilde{NTS}_{DM}$	0.075	0.52	0.48	0	0	0
	$\widetilde{NTS}_{SA}$	0.155	0.36	0.64	0	0	0
	$\widetilde{NTS}_{CS}$	0.234	0.10	0.40	0.45	0.05	0
	$\widetilde{NTS}_{T\&L}$	0.536	0	0	0.36	0.52	0.12
Aggregation result			0.08	0.17	0.34	0.34	0.08

Table II.43 Aggregation of Fitness & Strength (F&S) sub-criteria

Fuzzy output		Weight	Linguistic terms				
			Fit	Good	Moderate	Bad	Unfit
Pilot 3	$\widetilde{F\&S}_{OA}$	0.049	0	0	0	0.40	0.60
	$\widetilde{F\&S}_{HI}$	0.558	0	0	0.90	0.10	0
	$\widetilde{F\&S}_{BS}$	0.393	0	0	0.72	0.24	0.04
Aggregation result			0	0	0.85	0.13	0.02

Table II.44 Aggregation of pilot reliability (PR) main criterion

Fuzzy output		Weight	Linguistic terms				
			V. High	High	Moderate	Low	V. Low
Pilot 3	PR_{TP}	0.045	0.75	0	0	0	0.25
	PR_{PF}	0.186	0	0.02	0.19	0.45	0.34
	PR_{NTS}	0.606	0.11	0.17	0.30	0.27	0.14
	$PR_{F\&S}$	0.163	0	0.08	0.76	0.10	0.05
Aggregation result			0.10	0.13	0.34	0.27	0.16

II.3.4 Obtaining a pilot’s 3 reliability using utility techniques

The result obtained from the aggregation of the 4 main criteria for each pilot, as shown on previous section, shows this is not a straightforward way to obtain a crisp reliability value for the assessed pilot. The aggregation process for Pilot 3's reliability is identified as follows:

$\widetilde{PR}$ = {(Very High, 0.10), (High, 0.13), (Moderate, 0.34), (Low, 0.27), (Very Low, 0.16)}

The fuzzy terms used to express the goal use five linguistic variables, where the highest preference term used is (Very High) while the lowest linguistic preference used is (Very Low). The utility value for assessing the reliability of a marine pilot can be identified as 0.6298, using equations (6.16-6.21), as presented in Table (II.45).

Table II.45 The reliability value for Pilot 3

H_n	Very High	High	Moderate	Low	Very Low
V_n	5	4	3	2	1
$u(H_n)$	$\frac{5-1}{5-1}=1$	$\frac{4-1}{5-1}=0.75$	$\frac{3-1}{5-1}=0.5$	$\frac{2-1}{5-1}=0.25$	$\frac{1-1}{5-1}=0$
β_n	0.10	0.13	0.34	0.27	0.16
$\sum_{n=1}^{5}\beta_n$	$= 0.10+0.13+0.34+0.27+0.16=1 \longrightarrow \beta_H = 0$				
$\beta_n u(H_n)$	0.098	0.096	0.172	0.068	0
The reliability value for Pilot 3 = $\sum_{n=1}^{5}\beta_n u(H_n)$= 0.4341					

II.3.5 Sensitivity analysis

Table II.46 Decrement of lower preference value for technical proficiency (TP) sub-criteria

	Decrement	Linguistic terms				
		V. Good	Good	Average	Low	Basic
$\widetilde{TP}_{QPL}$	Main	0	0	0	0	1
	0.1	0.1	0	0	0	0.9
	0.2	0.2	0	0	0	0.8
	0.3	0.3	0	0	0	0.7
$\widetilde{TP}_{ST}$	Main	0	0	0	0	1
	0.1	0.1	0	0	0	0.9
	0.2	0.2	0	0	0	0.8
	0.3	0.3	0	0	0	0.7
$\widetilde{TP}_{WEx}$	Main	1	0	0	0	0
	0.1	1	0	0	0	0
	0.2	1	0	0	0	0
	0.3	1	0	0	0	0

Table II.47 Decrement of lower preference value for personal fatigue (PF) sub-criteria

	Decrement	Linguistic terms				
		Neutral	S. Fatigues	Moderate	Fatigued	V. Bad
$\widetilde{PF}_{WH}$	Main	0	0	0	0.24	0.76
	0.1	0.1	0	0	0.24	0.66
	0.2	0.2	0	0	0.24	0.56
	0.3	0.3	0	0	0.24	0.46
$\widetilde{PF}_{WS}$	Main	0	0	0.32	0.56	0.12
	0.1	0.1	0	0.32	0.56	0.02
	0.2	0.2	0	0.32	0.48	0
	0.3	0.3	0	0.32	0.38	0
$\widetilde{PF}_{WEnv}$	Main	0	0	0.24	0.62	0.14
	0.1	0.1	0	0.24	0.62	0.04
	0.2	0.2	0	0.24	0.58	0
	0.3	0.3	0	0.24	0.48	0

Table II.48 Decrement of lower preference value for non-technical skills (NTS) sub-criteria

	Decrement	Linguistic terms				
		V. Good	Good	Moderate	Bad	V. Bad
$\widetilde{NTS}_{DM}$	Main	0.52	0.48	0	0	0
	0.1	0.62	0.38	0	0	0
	0.2	0.72	0.28	0	0	0
	0.3	0.82	0.18	0	0	0
$\widetilde{NTS}_{SA}$	Main	0.36	0.64	0	0	0
	0.1	0.46	0.54	0	0	0
	0.2	0.56	0.44	0	0	0
	0.3	0.66	0.34	0	0	0
$\widetilde{NTS}_{CS}$	Main	0.1	0.4	0.45	0.05	0
	0.1	0.2	0.4	0.40	0	0
	0.2	0.3	0.4	0.3	0	0
	0.3	0.4	0.4	0.2	0	0
$\widetilde{NTS}_{T\&L}$	Main	0	0	0.36	0.52	0.12
	0.1	0.1	0	0.36	0.52	0.02
	0.2	0.2	0	0.36	0.44	0
	0.3	0.3	0	0.36	0.34	0

Table II.49 Decrement of lower preference value for fitness & strength (F&S) sub-criteria

Decrement		Linguistic terms				
		Fit	Good	Moderate	Bad	Unfit
$\widetilde{F\&S}_{OA}$	Main	0	0	0	0.4	0.6
	0.1	0.1	0	0	0.4	0.5
	0.2	0.2	0	0	0.4	0.4
	0.3	0.3	0	0	0.4	0.3
$\widetilde{F\&S}_{HI}$	Main	0	0	0.9	0.1	0
	0.1	0.1	0	0.9	0	0
	0.2	0.2	0	0.8	0	0
	0.3	0.3	0	0.7	0	0
$\widetilde{F\&S}_{BS}$	Main	0	0	0.72	0.24	0.04
	0.1	0.1	0	0.72	0.18	0
	0.2	0.2	0	0.72	0.08	0
	0.3	0.3	0	0.70	0	0

According to the above increment and decrement process, the utility value for the goals in accordance to these changes are presented on Table (II.49), and a graph is drawn on Figure II.8.

Table II.49 Alteration of the median of Pilot 3's reliability due to lowest preference decrement

Sub-criterion	**Alteration of the median reliability value of a pilot's duo to the following decrease in the degree of belief associated to the lowest preferences linguistic term of the median fuzzy set of each sub-criterion**			
	Main	**- 0.1**	**- 0.2**	**- 0.3**
QPL	0.4341	0.4343	0.4345	0.4347
ST	0.4341	0.4348	0.4355	0.4362
WEx	0.4341	0.4341	0.4341	0.4341
WH	0.4341	0.4360	0.4379	0.4399
WS	0.4341	0.4384	0.4421	0.4457
WEnv	0.4341	0.4396	0.4449	0.4496
DM	0.4341	0.4347	0.4352	0.4358
SA	0.4341	0.4355	0.4369	0.4382
CS	0.4341	0.4435	0.4497	0.4559
T&L	0.4341	0.4847	0.5274	0.5679
OA	0.4341	0.4344	0.4346	0.4348
HI	0.4341	0.4391	0.4416	0.4443
BS	0.4341	0.4368	0.4393	0.4416

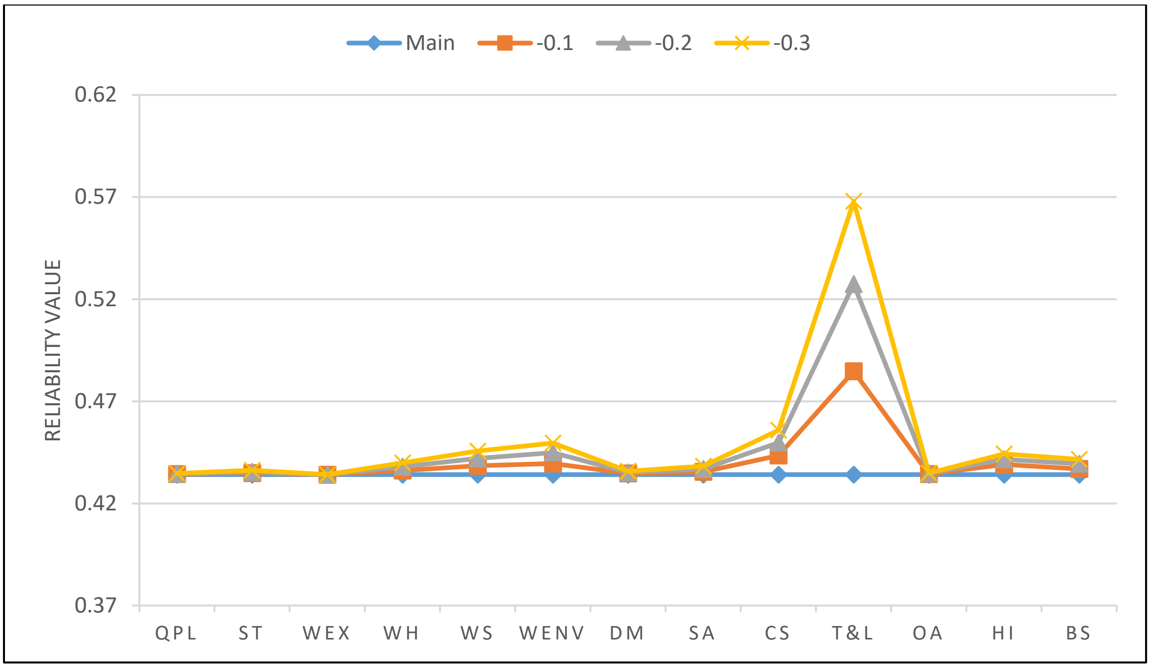

Figure II.8 Model sensitivity output for Pilot 3