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Study on the assessment of seafarers' fatigue

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STUDY ON THE ASSESSMENT OF SEAFARERS' FATIGUE

By

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DECLARATION

I certify that all the material in this dissertation that is not my own work has been identified, and that no material is included for which a degree has previously been conferred on me.

The contents of this dissertation reflect my own personal views, and are not necessarily endorsed by the University.

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ABSTRACT

Title of dissertation: **Study on the Assessment of Seafarers' Fatigue**

Degree: **MSc**

Global concern about the issue of fatigue at sea is widely evident across the shipping industry. Fatigue-induced human errors have been identified as major contributing factors in most maritime accidents. This paper attempts to explore an approach to evaluate the degree of seafarers' fatigue and to propose some suggestions on fatigue prevention and management.

According to the definition given by the IMO, Fatigue is a state of feeling tired, weary, or sleepy that results from prolonged mental or physical work, extended periods of anxiety, exposure to harsh environments, or loss of sleep. The effects of fatigue are impaired performance and diminished alertness.

In this study, the definition and effects of fatigue at sea are first examined, followed by a review of fatigue-induced maritime incidents and the prevalence of fatigue in the maritime industry. The factors affecting navigation officers' fatigue are categorized into four groups in this study: crew-specific factors, management factors, ship-specific factors and environmental factors.

The evaluation index system and weight of evaluating indexes are determined by applying the AHP. Efforts are made to develop an evaluation model for seafarers' fatigue with the application of multi-level fuzzy comprehensive evaluation. Consequently, recommendations on supervision and prevention of fatigue onboard ships are proposed for maritime organizations, shipping companies and seafarers.

KEYWORDS: Seafarers, Fatigue, AHP, Fuzzy Comprehensive Evaluation, Recommendations

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LIST OF ABBREVIATIONS

AHP   Analytic Hierarchy Process

AIS   Automatic Identification System

BRM   Bridge Resources Management

BTM   Bridge Team Management

ECDIS   Electronic Chart Display and Information System

EEG   Electroencephalogram

HSE   Health and Safety Executive

ILO   International Labor Organization

IMO   International Maritime Organization

ISM Code   International Safety Management Code

ISPS Code   The International Ship and Port Facility Security Code

ITF   International Transport Workers' Federation

MAIB   Marine Accident Investigation Branch

MLC   Maritime Labor Convention

MSC   Maritime Safety Committee

MSLT   Multiple Sleep Latency Test

NASA   National Aeronautics and Space Administration

NTSB   National Transportation Safety Board

RSCWR   Railways (Safety Critical Work) Regulations

SIRC   Seafarers International Research Centre

SOLAS   International Convention for the Safety of Life at Sea

US   United States

UK   United Kingdom

Chapter I Introduction

1.1 General remarks

"Shipping is perhaps the most international of all the world's great industries, and also one of the most dangerous" (IMO, 2011). A range of approaches have been introduced to enhance maritime transport safety, such as developing new methods of transportation, introducing numerous technical innovations, increasing traffic surveillance and control, etc. Nevertheless, accidents with catastrophic consequences still happen, which implies that all these measures are not sufficiently effective.

Fatigue has been identified as a major contributing factor in numerous maritime accidents, such as EXXON VALDEZ (Raby and McCallum, 1997) and HERALD OF FREE ENTERPRISE (Wellens et al., 2005). In the competitive 24-hour industry where shift work and long working hours are common, the potential for fatigue at sea is extremely great. It is illustrated in some recent publications that seafarers' fatigue is common and widespread (Smith, et al., 2006; Smith, 2007; Allen, et al, 2008). Moreover, fatigue can cause more hazardous impacts on the shipping industry than elsewhere because of the specific characteristic of seafaring. Industry participants such as maritime regulators, ship-owners, trade unions and P & I clubs have reached the consensus that fatigue onboard is common in the marine industry and it is necessary to make joint efforts to deal with the issue.

Generally considered as a hotspot issue in the shipping industry, fatigue among

seafarers has received a growing global concern (Patraiko, 2006) and has been subject to many studies in recent years. In 1989, a review (Brown, 1989) exploring the relationship between working hours, fatigue and safety at sea was published. The author considered inadequate reporting systems as the main reason why this problem was overlooked in legislative channels as few accident cases cited fatigue as a direct causal factor. Eleven years later, a similar conclusion was made in a review focused on the British offshore oil support industry, which concluded that fatigue had been noticeably under-investigated in the maritime domain (Collins, 2000).

A proactive approach in fatigue management (Reyner and Baulk, 1995) was provided in 1995 by Reyner and Baulk after their study on technical data of fatigue among seafarers. A study at the Seafarers International Research Centre (1996) also addressed the fatigue issue in terms of identifying important elements for further research and analyzing the unresolved components of fatigue itself. In 1997, a group of experts (Parker, et al., 1997) studied the health and lifestyle behaviors of seafarers, which turned into an efficient fatigue investigation. Recently, the IMO issued the foremost important document addressing fatigue issues "Guidance on Fatigue Mitigation and Management"[1] (IMO, 2001), which directly tackles the issue of fatigue at sea.

A number of research projects are being undertaken in the UK, the US, Sweden and doubtless in other places too. A €3.78 million European Commission-funded 30-month research initiative known as Project Horizon[2] was launched in 2009 to investigate and tackle the problems posed by seafarer fatigue (Warsash Maritime Academy, 2009). Developed and led by Warsash Maritime Academy, the project brought together 11 academic institutions and organizations from the shipping industry, seeking to improve safety at sea by developing a fatigue management

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[1] See MSC/Circ.1014.
[2] For detailed information, please visit Warsash Maritime Academy website:
http://www.warsashacademy.co.uk/research/horizon/horizon.aspx

toolkit for the industry, as well as proposing recommendations for improving work patterns at sea (Practical Boat Owner, 2009).

Although many studies and research projects concerning fatigue have been undertaken in recent years, there are so far no effective or sufficient measures to deal with the problem because of sophisticated challenges, and lack of knowledge. The complexity and difficulty posed by the fatigue issue today in the shipping industry reveal the need for further research. Considering also the permanent effect and the potential hazard that fatigue factors are posing to seafarers, additional studies need to be undertaken in order to find more effective solutions to the problem. Lessons can be learned from manufacturing industries and other transport sectors, which have a long history of research on human fatigue and fatigue-induced incidents (Allen, Wadsworth and Smith, 2008).

1.2 Objectives of the dissertation

The primary objective of this research is to tackle the issue of fatigue at sea and establish an evaluation model for seafarers' fatigue that can be universally applied in the shipping industry. The subsequent purpose is to give a general understanding of fatigue, which includes its definition, the contributing factors and its effects in the maritime domain. The prevalence of fatigue and the relationship between fatigue and maritime accidents are also to be examined. Other general aims include proposing a number of recommendations to seafarers, shipping companies and policy makers so as to combat the issue of fatigue efficiently in the maritime industry.

1.3 Hypotheses of the dissertation

In order to achieve the aim previously declared, the research of the dissertation is carried out mainly based on several hypotheses that concern the basic premises of

this study. These hypotheses are mainly related to the qualification of the seafarers to be assessed. The first hypothesis is that the seafarers are physically and mentally healthy, which means that the requirements for the physical examination in STCW are fully fulfilled. In other words, the factors of illness and sickness will be excluded in the process of evaluation. The second hypothesis is that there are no significant changes in their families, which means that no distressing family events happen during their absence. So the factor of stress from family is excluded too. The third hypothesis is that accidental factors, such as participation of search and rescue of distressed vessels, should be excluded.

1.4 Methodology of the dissertation

The methodological approach of this thesis is to combine a series of techniques to explore risk factors for fatigue, collect data and make assessments on seafarers' fatigue. The relevant literature was widely reviewed beforehand, including articles from contemporary journals, books, international conventions, appropriate IMO documents and circulars, and validated information from websites. The statistical figures of accidents were collected and analyzed to address the prevalence of fatigue at sea. Furthermore, opinions were exchanged and advice was taken by visiting various shipping entities during field-study trips and by sending emails. Finally, the Analytic Hierarchy Process and fuzzy mathematics were used to analyze the risk factors for fatigue and establish the evaluation model on seafarer fatigue.

1.5 Structure of the dissertation

The dissertation consists of six chapters. In order to have a comprehensive analysis of fatigue, relevant information regarding the definition of fatigue, its effect upon seafarers and the prevalence of fatigue at sea is first examined in chapter two.

In chapter three, the contributing factors to fatigue are analyzed and the evaluation index system of seafarers' fatigue is established. A model for the evaluation of seafarers' fatigue is established and applied in chapter four. Chapter five proposes a number of recommendations on the prevention and management of fatigue at sea. Finally, overall conclusions are made in the last chapter. The structure and research approaches of the dissertation are clearly illustrated in figure 1.1.

Analysis of contributing factors for fatigue	
(Literature review)	(Expert inquiry)

Evaluation index system and weight of indexes
(the AHP)

Evaluation model
(Fuzzy Comprehensive Evaluation)

Case study

Recommendations		
Maritime organizations	Shipping companies	Seafarers
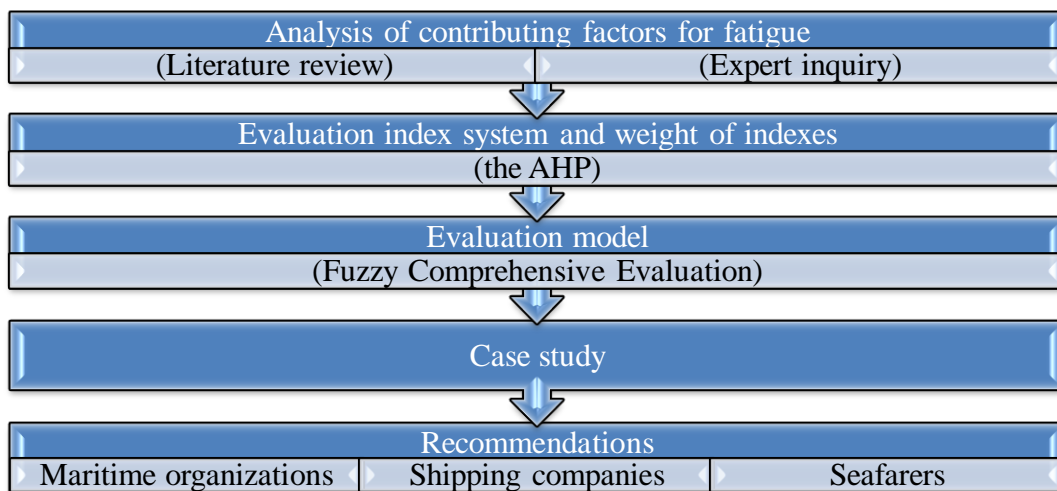
Figure 1.1 Structure and methodology of the dissertation

Chapter II   Understanding fatigue at sea

2.1 Definition of fatigue

The word "fatigue" is used to describe a range of disorders and sufferings in many fields. However, there is no universally accepted technical definition for fatigue. It is generally described as a state of feeling tired, weary, or sleepy that results from prolonged physical or mental work, extended periods of anxiety, exposure to harsh environments, or loss of sleep (IMO, 2001).

As to the definition of fatigue at sea, the following definition is found in IMO's MSC/Circ.813/MEPC/Circ.330, List of Human Element Common terms:

"A reduction in physical and/or mental capability as the result of physical, mental or emotional exertion which may impair nearly all physical abilities including: strength; speed; reaction time; coordination; decision making; or balance (IMO, 1999)".

Generally, fatigue occurs when the balance is lost between the physical and mental effort used during all waking activities and the recovery of the body and brain after that effort, as shown in figure 2.1. The aspects of recovery include getting enough sleep, eating and drinking properly, and taking short breaks when necessary.
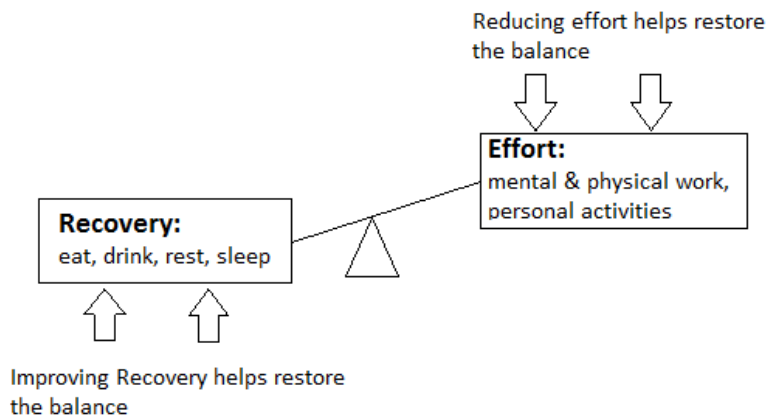
Figure 2.1 The mechanism of fatigue (Source: Fatigue advisor resource)

In literature, fatigue is mainly divided into two types: acute fatigue and chronic fatigue. Acute fatigue is a normal phenomenon that disappears after a period of rest. Chronic fatigue is caused by the prolonged accumulation of acute fatigue. The compensation mechanisms are not as useful in reducing chronic fatigue as in reducing acute fatigue. A wide variety of symptoms of fatigue are observed, which include:

Increased anxiety, decreased short-term memory, slowed reaction time, decreased work efficiency, reduced motivational drive, decreased vigilance, increased variability in work performance, increased errors of omission which increase to commission when time pressure is added to the task and increased lapse with increasing fatigue in both number and duration (Battelle Memorial Institute, 1998).

2.2 Effects of fatigue on seafarers

Fatigue is a common symptom of various illnesses, and can even be observed in healthy individuals (Pawlikowska, et al, 1994; Watanabe, 2008). Among the general working population, fatigue has been associated with accidents and injuries (Bonnet and Arand, 1995; Hamelin, 1987). There is also a clear link between fatigue and ill health (Andrea, et al, 2003; Folkard, et al, 2005; Huibers, et al, 2004; Leone, et al,

2006), as well as impaired work performance (Charlton and Baas, 2001), sick leave and disability (Janssen, et al, 2003; van Amelsvoort, et al, 2002).

Fatigue is a common problem for all 24-hour day transportation modes and industries. The effects of fatigue at sea are particularly dangerous due to the specialized nature of seafaring, which requires constant alertness and intense concentration from its workers. What's more, other unique aspects of seafaring such as long periods away from home, limited communication among colleagues and consistently high workloads, separate it from other industries. Working in these circumstances, the seafarers' health, even their life-span, may be affected by fatigue and impaired performance (Smith, 2007). In the IMO document 'Guidelines on fatigue'[3], some of the possible effects of fatigue are listed in terms of the performance impairments and the symptoms associated with them.

It has been revealed that fatigue has a confirmed detrimental effect on alertness which means the working state of the brain drops when making conscious decisions (IMO, 2001). For a seafarer, diminished alertness means a longer time is needed to respond to signals, difficult situations and other tasks aboard ship. Furthermore, "a decline in alertness will lead to reallocation of attention to central features rather than minor ones" (Cardiff University, 1996, p.34). In terms of this consideration, the concentration and sustainable attention of the seafarer will be significantly impaired. As a result, negatively impacted alertness can lead to drastically reduced work performance in terms of physical, psychological and mental aspects (IMO, 2001).

Fatigue's effects on work performance have been identified by many studies and research projects (Smith, 1999), among which four major effects are summarized as follows:

(a) The first effect is the individual's reduced awareness and poor memory causing the loss of information, data and the ignorance of operating steps.

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[3] See MSC/Circ 1014, Module 3 and Module 4

Fatigued seafarers may become more susceptible to errors of memory.

(b) The second effect is the high degree of risk undertaken by the seafarer in difficult tasks during the voyage. A fatigued seafarer usually selects strategies that have a high degree of risk on the basis that they require less effort to execute, which might subsequently lead to wrong decisions.

(c) The third effect is that fatigue can impact an individual's initiatives to react to the driving force in the work. A fatigued seafarer may become less motivated in their job contributing consequently to poor performance at work.

(d) The last effect is that it can impact a seafarer's ability in problem-solving and decision-making which are essential for the seafaring task (IMO, 2001).

In summary, fatigue can affect seafarers' health possibly by increasing risk of chronic disease, and can pose a potential threat to their life and ship's safety by drastically reducing their alertness levels and impairing their job performance.

2.3 Prevalence of fatigue

Fatigue is a common problem in the general population (Bensing, et al, 1999; David, et al, 1990). It is well known that stressful social events frequently lead to acute mental fatigue and sometimes cause problems with mental health and chronic fatigue, even resulting in death in the case of overwork (Amagasa, et al, 2005; Ke, 2012; Iwasaki, et al, 2006). Prevalence of fatigue in the general working population has been estimated to be as high as 22% (Bültman et al., 2002). Considerable onshore studies on fatigue show that as much as 20% of the working population experience extreme fatigue in their life (Smith, 2007). In Japan, 60% of the general adult population complains of fatigue and one third of the population suffers from chronic fatigue (Watanabe, 2008).

Fatigue was regarded as the first concern of seafarers in a study concerning ship

manning (National Research Council, 1990). It was also the most frequently mentioned problem in a recent US Coast Guard report on human error in the maritime transportation system (U.S. Coast Guard, 1995). The US Coastguard study estimated that 16% of critical vessel accidents and 33% of personal injury accidents were caused by fatigue directly or indirectly (McCallum, et al, 1996). It was also found in the study that fatigue's contribution to groundings and to collisions was 36% and 25% respectively (McCallum, et al, 1996). However, the values were much higher in another Japanese study: 53% for groundings and 38% for collisions (Det Norske Veritas, 1999). The deviations of the results are probably caused by the difference of the source and size of these statistical data of accidents.

In an interview (Wellens et al, 2005) with seafarers on their collision experience, it was found that fatigue was a potentially important contributory factor to the high incidence of these accidents. A group of researchers found that fatigue might be a causal factor in between 11% and 23% of collisions and groundings when they reviewed the accident literature (Houtman, et al., 2005). But such estimates were difficult because of the lack of systematic reporting procedures (Gander, 2005). In a survey (Wadsworth et al., 2008) of over 1,800 professional seafarers, a quarter of respondents reported fatigue or sleep while on watch and nearly half of the sample reported that fatigue leads to reduced collision awareness.

A great amount of research has shown that fatigue is still a major issue at sea. However, estimates of the prevalence of fatigue will vary depending on the indicator of fatigue we choose. Different aspects of the fatigue process will lead to different results. It is also suggested that seafarers may be unlikely to admit and report their experience of fatigue in the investigations due to the worry of being derided (Houtman, et al, 2005).

2.4 Fatigue and maritime disasters

Although fatigue had been perceived as a causal factor in maritime accidents, it was not until the occurrence of the *Exxon Valdez* accident that the outmost attention of the industry was triggered to this issue. During its navigation near the coast of Alaska, the US tanker *Exxon Valdez* got stranded on Bligh Reef on March 24th, 1989 (Cardiff University, 1996). The US National Transportation Safety Board carried out the investigation after the accident, which identified fatigue as the major contributor to this accident. The investigation also cited that "there were no rested officers to stand the navigation watch during the voyage" (Lützhöft, 2007).

Fatigue's negative effect in the process of maritime accidents was also demonstrated by another casualty----the grounding of *Cittas* in the English Channel. In 1997, the German-owned container ship ran aground off the coast of the Channel leading to damage to the ship and pollution of the environment. Fatigue was found to be the primary cause of the grounding, the same cause found in the *Exxon Valdez* accident. The investigation revealed that the watch-keeper was severely sleep-deprived, resulting in the accident (Reyner & Baulk, 1998).

More recent accidents caused by the factor of fatigue are the cases of the vessel *Jambo* off the coast of Scotland in 2003 (Marine Accident Investigation Branch, 2004), and the grounding of *Antari* on the coast of Northern Ireland in 2008 (MAIB, 2009). A common feature found in both cases was fatigued officers on watch. In the first case the watch keeping officer missed course alteration because of his impaired performance caused by fatigue, while in the second case the officer of the watch had fallen asleep shortly after taking over the watch at midnight. Both accidents caused destructive consequences, not only environmental damage but also loss of property and innocent lives.

Even though more stringent measures and regulations are adopted, the same story

repeats again and again, such as the grounding of the Bahamas-flagged *Crete Cement* on the south-eastern tip of Aspond Island in 2008 (Maritime Accident Casebook, 2010), and the grounding of Chinese registered bulk carrier *Shen Neng 1* on Douglas Shoal in 2010 (gCaptain, 2010). Investigations into these accidents revealed that fatigue played an important role in both casualties.

2.5 Rules and regulations concerning fatigue at sea

There is a list of regulations to manage the risk of fatigue in many industries. Significant contributions have been made by conventions adopted by the IMO and the ILO in terms of the prevention of tiredness and fatigue at sea.

2.5.1 The ILO instruments

The following ILO instruments concern fatigue related aspects:

(a) Convention No. 180

This convention introduces provisions to establish limits on seafarers' maximum hours of work or minimum hours of rest so as to reduce fatigue and increase work capability of the crew.

(b) Maritime Labour Convention, 2006[4] (MLC, 2006)

The MLC, 2006 contains limits on hours of work and hours of rest that are consistent with those in ILO 180. The convention applies to all seafarers and will replace ILO convention 180 when it comes into force.

(c) Other Conventions

Other ILO Conventions related to fatigue include the following convention numbers: 92, 133, 140, 141 and 147. Each introduces minimum habitability requirements on board ships, such as noise control and air conditioning.

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[4] It hasn't come into force yet. To come into force, the MLC has to be ratified by at least 30 member States with a total share in the world gross tonnage of ships of 33 percent.

2.5.2 The IMO instruments

The IMO instruments concerning fatigue related aspects are listed as follows:

(a) Conventions and Codes

The STCW Convention requires administrations to establish and enforce rest period requirements for watch-keeping personnel so as to prevent fatigue. In addition, there are also requirements on minimum periods and frequencies of rest in the convention. Part A of the STCW Code requires posting of watch schedules while Part B recommends record-keeping.

The ISM Code introduces safety management requirements for ship-owners to ensure safety at sea. The code has some specific requirements on fatigue management, such as manning of ships with qualified and medically fit personnel, familiarization and training for shipboard personnel, and so on. Besides these primary conventions and codes, there are other codes addressing fatigue management for specific types of ships, such as the International Code of Safety for High Speed Craft.

(b) Assembly Resolutions

Besides the STCW Convention and the ISM Code, the IMO has adopted many resolutions regarding fatigue at sea, such as Resolution A.481(XII)27 (Principles of Safe Manning), Resolution A.772(18) (Fatigue Factors in Manning and Safety), and Resolution A.792(19) (Safety Culture In and Around Passenger Ships).

(c) Maritime Safety Committee (MSC) Circulars

A lot of circulars have been adopted by the MSC of the IMO, such as MSC/Circ.493 (Recommendation Related to the Fatigue Factor in Manning and Safety), MSC/Circ.565 (Fatigue as a Contributory Factor in Maritime Accidents), MSC/Circ.621 (Guidelines for the investigation of accidents where fatigue may have been a contributory factor), and so on.

2.6 Overview of fatigue research in other transport sectors

There is a long history of fatigue research in other transport sectors, with more concern on the study of fatigue in road transport (Crawford, 1961; Brown, 1997). It is generally agreed that the issue of fatigue in transport sectors has previously been underestimated (Akerstedt and Haraldasson, 2001) and appropriate strategies for the prevention and management of fatigue are required.

2.6.1 Fatigue research in road transport

It is confirmed by a mass of strong evidence that fatigue increases the risk of road accidents (Connor, et al, 2001; Hakkanen and Summala, 2000). Most previous fatigue research in road transport was based on the situation of the USA, Europe and Australia, but recent studies are likely to expand to cover many other countries, such as Greece, Israel and Norway (Tzamalouka, et al, 2005; Sabbagh-Erlich, 2005; Sagberg, 1999).

A series of studies by the National Transportation Safety Board (NTSB) in the USA have perceived sleepiness as a contributing factor in accidents involving heavy vehicles (Wang and Knipling, 1994). In 1990, the NTSB study indicated that 31% of fatal accidents were caused by fatigue (NTSB, 1990). Another NTSB study in 1995 concluded that more than half of single vehicle accidents were fatigue-related, including accidents of heavy trucks (NTSB, 1995). In 2007, the New Zealand Transport Agency (McKernon, 2008) identified fatigue as a contributing factor in 48 fatal crashes, 130 serious-injury crashes and 554 minor-injury crashes in New Zealand.

Recent research results indicate that prolonged working hours and sleep deprivation are the major causes of road transport accidents (Jackson, et al., 2011). Other risk factors for effects of fatigue on driving include increased day time

sleepiness (Haraldsson, et al, 1990), changes in circadian rhythm (Philip, et al, 1996; Phillip, et al, 1999), working at night (Hamelin, 1987) and combinations of sleep loss and alcohol (Keall, et al, 2005). Organizational factors are also related to the frequency of road accidents. For example, a study by Goodwin found that the frequency of crashes increased as truck fleet size decreased (Goodwin, 1996).

The measures dealing with fatigue-induced accidents include changing work patterns and introducing naps or rest breaks (Landstrom, et al, 2004). Another approach is to use technological devices to detect fatigue and give visual or audible warnings to the drivers (Dinges and Mallis, 1998; Lal, et al, 2003). The Circadian Alertness Simulator[5] has been developed as a practical tool for assessing the risk of diminished alertness at work (Moore-Ede, et al, 2004). Modeling of fatigue has also been carried out in some countries (Belyavin and Spencer, 2004; Van Dongen, 2004). Some maritime organizations have even launched training in fatigue awareness and fatigue management. However, each of these measures merely mitigates fatigue in some way and a combination of measures should be taken for the effective management of fatigue.

2.6.2 Fatigue research in rail transport

Research on fatigue and railway operations has been undertaken for many years (Grant, 1971), mainly focusing on the relationship between fatigue and critical railway accidents (Buck and Lamonde, 1993). Studies using train simulators have shown that fatigue can adversely affect train drivers' performance (Roach, et al, 2001). The impact of fatigue in rail transport has been confirmed by studies from Poland and China (Malgarzeta, 1982; Zhou, 1991). In the US Federal Railroad Administration's Fatigue Research Program, the potential for fatigue in the rail

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[5] For more information about the Circadian Alertness Simulator, see the article "Circadian alertness simulator for fatigue risk assessment in transportation: application to reduce frequency and severity of truck accidents".

industry was reviewed (Sussman and Coplen, 2000), which eventually promoted co-operation between government, unions and industry, leading fatigue research in rail transport to a new era.

In the UK, the HSE[6] Fatigue index (Spencer, et al, 2006) has been applied to the railway industry (Stone, et al, 2005), which is considered as an achievement in rail fatigue research. Diary studies of factors influencing fatigue were carried out in the research, resulting in the development of a good practice guide for drivers to help them cope with shift work and fatigue. There is a specific code of practice on managing fatigue in safety critical work within the UK's railway safety legislation, namely the Railways (Safety Critical Work) Regulations 1994 (RSCWR). Some other countries have developed similar approaches (Sherry, 2005).

2.6.3 Fatigue research in air transport

Fatigue has been considered as a major potential problem in the air-traffic sector and fatigue-related accidents have also been reported in the air transport industry (Philip and Akerstedt, 2006). Research on fatigue in aircrew can be traced back to the Second World War. It is clearly indicated from the results of these early studies that prolonged flying resulted in performance decrements (Welford, et al, 1950). Problems of fatigue in aircrew have become much greater since the introduction of long haul flights (Cameron, 1971; Grandjean, et al, 1971).

The NASA-Ames research group has undertaken a systematic series of studies examining flight crew fatigue in commercial pilots (Gander, et al, 1998a, 1998b, 1998c). Sleep, circadian rhythms and fatigue were measured before and after scheduled commercial flights in these studies. A lot of modern technologies were applied to detect fatigue in recent research, such as eye movement recording and

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[6] For details about HSE, please visit: http://www.hse.gov.uk

EEG (Wright, et al, 2005). In another study a warning device linked to a sensor measuring wrist inactivity was developed to prevent unwanted sleepiness. Similar to other industries, the aircraft industry has also developed its own fatigue risk management systems, such as the FRMS Toolbox[7] for Canadian Aviation.

2.7 Concluding remarks

Pursuant to the above, an overview of the general information on fatigue was considerably scrutinized. Different definitions of fatigue were listed before the introduction of the IMO definition of fatigue at sea, which defines seafarer fatigue as a reduction in physical and/or mental capability as the result of physical, mental, or emotional exertion. Fatigue not only has an adverse effect on the physical and mental wellbeing of crew members, it also has close relationship with the safety of property and life at sea. An in-depth literature review demonstrated that fatigue was alive and common in the maritime industry. Fatigue is now widely perceived as a major contributing factor for numerous marine casualties. Both the IMO and the ILO have established a variety of instruments to address this issue. At the end of this chapter, the development of fatigue research in other transport sectors was reviewed so as to find some example methods that can be applied in the seafaring industry.

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[7] For more details, please visit: http://www.tc.gc.ca/eng/civilaviation/standards/sms-frms-menu-634.htm

Chapter III   Evaluation index system of seafarers' fatigue

Fatigue is a complex issue consistently associated with poor quality sleep, high stress, and negative environmental factors. In the case of seafaring, other important factors include frequent port turn-around, prolonged working hours, low job support and personal characteristics. It is generally accepted that fatigue is the consequence of the combined effect of these contributing factors. All these factors will be analyzed and an evaluation index system will be established in this chapter.

3.1 Risk factors for fatigue at sea

A broad range of risk factors covering all areas from company organization to environmental conditions, personal characteristics and legislation have been identified as contributing factors to fatigue. Many of these established risk factors for fatigue are clearly relevant to seafarers. The most common causes for seafarers' fatigue are lack of sleep, high stress and excessive workload. Certainly, there are many other contributors depending on specific circumstances.

It is recognized that seafarers are often exposed to risk combinations that lead to impaired performance and reduced well-being (Wadsworth, et al., 2008). The causes of fatigue can be categorized in many ways. For the sake of thoroughness and reasonableness, the IMO divided all relevant factors into four general categories[8] in

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[8] For detailed information, see MSC/Circ 1014.

2001 (IMO, 2001): crew-specific factors, management factors, ship-specific factors and environmental factors.

3.1.1 Crew-specific factors

Fatigue varies from one person to another due to individual attributes as well as circumstances. The crew-specific factors include but are not limited to personal habits, lifestyle, sleep and rest, stress, circadian rhythm and working hours.

(a) Sleep and rest

It is certain that sleep and rest are the most crucial elements affecting human fatigue and subsequent impaired work performance. However, there are a number of obstacles preventing seafarers from gaining sufficient restorative sleep. Working 24-hour shift patterns on a moving vessel, mariners might have to work additional hours and endure severe noise and vibration. What's more, they have to face unexpected disturbances from both crew and vessel activities.

For most people, any less than five hours sleep can lead to drowsiness the next day. In a study (Parker, et al., 1997) focused on the health, stress, and fatigue of Australian seafarers, almost half of the participants reported having only four to six hours of sleep a night while underway. In a study (Foo et.al, 1994) involving 20 male naval volunteers onboard a landing ship in the South China Sea, the issue of sleep deprivation of these crew members was investigated. The effect of sleep loss on manual tasks, which was tested with relation to the presence of activity in different sections of the cerebral cortex, emerged just 6-12 hours into the study. However, the impact on cognitive and perceptual skills did not arise until 30-36 hours, resulting in the impairment of normal watch-keeping (How, et al., 1994).

(b) Circadian rhythm

Each individual has a biological clock which regulates the body's circadian

rhythm. The biological clock within our bodies makes us sleepy or awake on a normal schedule no matter what we are doing (Cardiff University, 1996). Similarly, circadian rhythm represents various processes and states in our body over 24 hours. It affects many functions such as sleep behavior, hormone levels, body temperature and alertness level, as shown in figure 3.1. Although the circadian rhythm varies individually, the physiology of the human body is designed to be awake during daytime and sleep at night in normal conditions. However, this heavily conflicts with the working patterns of seafarers. Irregular schedules aboard ship caused mainly by crossing time zones and shifting rotations can lead to the disruption of circadian rhythm (IMO, 2001). Consequently, the unsynchronized circadian rhythm will adversely impact the quality and quantity of sleep, leading to the impairment of seafarers' performance at work (IMO, 2001).
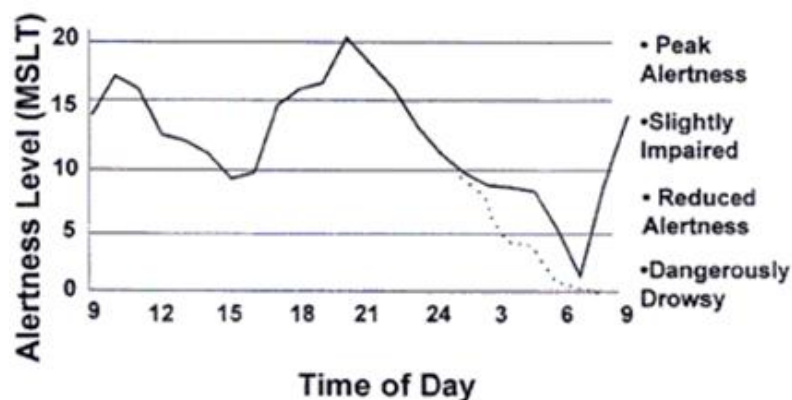
Figure 3.1 The normal circadian rhythm (source: www.rideforever.org)

(c) Stress

Stress is always considered as a complex issue because it affects seafarers' sleep quality and might lead to reduced alertness. Generally, the seafarer will feel stressed when he is confronted with an environment that poses a threat to him while being incapable of coping with it. As a result, working under pressure on a daily basis leads to the diminished work performance and health problems of seafarers. Stress aboard ship can be caused by a number of things, such as environmental hardships, personal

problems, interpersonal relationships and so on (IMO, 2001).

(d) Working hours

In an International Transport Federation (ITF) survey (ITF, 1998) involving 2,500 seafarers from 60 different nationalities, it was found that long working hours were very common among those participants. One fourth of the respondents reported that their average working hours were more than 80 hours a week. Long periods of continuous watch keeping were also reported, with 17% stating that their watch regularly exceeded 12 hours (ITF, 1998). More than 80% of the sample reported that the level of fatigue grew with the increase of the tour of duty. However, it is challenging to regulate working hours in the maritime sector because the workplace onboard is not simply within the auditable range (Allen, 2006).

Many other crew-specific factors should also be taken under consideration as they can potentially cause fatigue. Some of these factors include age of seafarer, mental and emotional factors such as fear, monotony and boredom, physical conditions such as diet and illness (IMO, 2001), ingested chemicals such as alcohol, drugs and caffeine, and workload aboard ship and in ports (Patraiko, 2006).

3.1.2 Management factors

Management factors are closely related to the organization and operation of ships. These factors can potentially cause stress and increased workload, ultimately resulting in fatigue.

(a) Organizational factors

The organizational factors within the management of vessels are major contributors to the potential stress problems of seafarers. Employment policies and on-board training (e.g. BTM) are proved important because both inefficient employment policies and insufficient training can impact depressingly the operations

onboard which may cause stress and fatigue for the crew members.

In addition, tasks such as paperwork, schedule shifts and overtime work can have a significant impact on seafarers' fatigue leading to errors in work. New procedures designed to increase ship safety, such as ISM and ISPS procedures and their record keeping process, can bring extra workload for navigation officers. As to work schedules, different work shifts lead to different levels of fatigue. According to the research of the Project Horizon, it was found that the six hours on/six off regime was more tiring than the four hours on/eight off style. It was also found that disturbed off-watch periods produced significantly high levels of tiredness in both systems.

There is no doubt that the management style implemented onboard ships can significantly affect seafarers' fatigue. In this context, the harsh rules imposed by the company management style may sometimes generate stress for seafarers because these rules might conflict with the willingness of seafarers. Moreover, it is very difficult for seafarers to comply with all the existing regulations due to the harsh conditions onboard ships. Consequently, the effort for compliance with national/international rules and regulations becomes a source of stress, leading to fatigue and subsequent impairment of alertness. Finally, the daily maintenance of the ship is proved to be another heavy burden for the seafarers because of its hardship and frequency (IMO, 2001).

(b) Voyage and scheduling factors

The voyage and scheduling aspect, just like the organizational aspect, is an essential component within management factors. Regarding this matter, the scheduled time between ports arranged by shipping companies may be frustrating for the seafarers as such hectic schedules mean less time for relaxation in most cases. Furthermore, the seafarers are sometimes exposed to harsh weather and sea conditions due to the requirements of complying with the schedule. All these factors can result in stress, tiredness and fatigue.

Seafarers who normally work during the daytime will show signs of reduced alertness if they shift suddenly to work through the night. It will take several days for the body to properly adjust to a change in schedule. However, problems usually occur during the period of adjustment in the case of the abrupt shift.

For road haulage drivers, those who made the most deliveries were more fatigued. A similar trend was found when comparing seafarers with a small sample of drivers. Just like the situation of those drivers, the seafarers' fatigue was related to the number of port turnarounds (Smith, Allen and Wadsworth, 2006). In a study (Wadsworth, et al., 2006) on tour-based fatigue trends, it was found that fatigue increased most noticeably during the first week of duty, which indicated that travelling to the ship and adjusting to a new environment were related to fatigue.

3.1.3 Ship-specific factors

Ship-specific factors include ship design features that can cause or affect fatigue of seafarers. Some of these features can impact the workload onboard while others influence the crew's sleep quality and level of stress.

It is generally accepted that the level of automation is very important in terms of reducing workload, which may lead to the mitigation of fatigue. A high level of automation can facilitate the work of seafarers because it costs less time to accomplish a task and less effort to operate the equipment aboard ships. For example, automated control of loading/discharging systems can significantly lighten officers' and other ratings' workloads with reduced human errors. Moreover, it has been proved that the ship's equipment reliability is also an important factor affecting fatigue because most of the seafarers rely heavily on the equipment.

Generally speaking, the living conditions of old ships are less comfortable and less safe compared with those of new vessels. It is also widely perceived among

mariners that old ships are more difficult to operate and maintain, which impacts seafarers' fatigue to a certain extent. In consideration of the fact that sleep and rest are critical factors for good work performance, the comfortableness of the work and accommodation environment is vital in terms of fatigue mitigation. Furthermore, the ship's motion, such as rolling and pitching, also contributes to seafarers' fatigue due to its effect on the aggravation of tiredness (IMO, 2001).

3.1.4 Environmental factors

The seafarers' sleep may be disrupted due to physical discomfort caused by environmental factors. Furthermore, being continuously exposed to excess levels of environmental factors, the seafarers' fatigue as well as health will be affected greatly.

(a) The internal factors

Features like noise within the ship have been defined as important causes of fatigue at sea. Noise presents in most compartments of a ship, with the engine operation, ventilation as well as ship motion as the major sources of noise on board. In a survey (Omdal, 2003) of 11 Norwegian vessels aiming to identify harmful factors to health, it was found that exposure to noise was the most common problem identified by crew, with 44% of the sample reporting noise as a problem. Noise in the workplace can lead to physiological and physical impacts on seafarers, causing fatigue and negatively-impaired work performance. It also affects sleep patterns and decreases the restorative quality of rest, which greatly contributes to fatigue.

Another internal feature contributing to fatigue is vibration caused by machinery, marine equipment and the ship's response to the environment. The entire crew can be affected because vibrations resonate throughout the hull structure. Short-term exposure to these vibrations can lead to headaches, stress, and fatigue while long-term exposure leads to constant body agitation. Moreover, extra energy is

needed to maintain physical balance on a moving vessel, especially during harsh weather conditions. A ship's pitching and rolling motions mean that 15-20% extra effort might be required to maintain balance (IMO, 2001).

In a study (Ellis, et al, 2003) on the influence of both noise and motion, interviews with participants onboard 7 vessels in the short sea and coastal industry indicated that noise and motion were associated with their mood and performance. In addition to the factors mentioned above, seafarers' fatigue is also subject to other internal factors such as heat, cold and humidity mainly caused by the ship's engine and weather conditions. All the above internal features directly influence the fatigue of seafarers (IMO, 2001).

(b) The external factors

The second element within the environmental aspect is the external factor whose main features include port conditions, weather conditions, and vessel traffic. Presently, port conditions are becoming a vital source of stress for seafarers. They have become a problematic issue for ships and seafarers because of unpredictable work hours, additional burden of safety, increased inspections and high pressures for turnarounds (Patraiko, 2006).

The weather and sea conditions en route are another important factor which should not be overlooked. Harsh weather conditions can cause not only poor sleep and rest, but also stress, both of which can cause or increase fatigue. Similarly, the traffic density encountered by the vessel when it is en route is another aggravating factor leading to many problematic issues such as diminished alertness and impaired work performance (IMO, 2001).

3.2 Principles of setting evaluation index system of seafarers' fatigue

The first step in the evaluation of seafarers' fatigue is the establishment of an

evaluation index system, which reflects the characteristics of the contributing factors to fatigue. Several criteria should be observed in the process of establishing the corresponding evaluation index system.

(a) Objectivity

In the process of selecting an evaluation index, the principle of objectivity should be followed to ensure the veracity of data sources. The index system must be scientific, objective and reasonable, covering most of the factors affecting seafarers' fatigue. In order to guarantee the quality of the evaluation result, the index system of this paper was developed based on a thorough literature review of risk factors for fatigue, following a scientific process.

(b) Pertinency

The indexes selected should be pertinent so as to ensure the accuracy of the evaluation result. Analysis should be focused on the factors affecting seafarers' fatigue in the process of index selection. Since the paper aims to evaluate seafarers' fatigue, the characteristics of seafaring work, which is different from other professions, should be considered.

(c) Practicality

Fatigue risk factors are complicated and quite extensive, so the index system established should be operable and practical. The indexes should be independent and easy to be quantified. The whole evaluation system should be logical and simplified so that it is easy to operate. However, the index should effectively reflect the extent of fatigue through the calculation of data, which is independent from the subjective opinion of the person investigated.

(d) Harmlessness

The indexes selected should not bring any harm to the person assessed. The process of evaluation should not lead to any negative psychological impact on the person. And the survey should not disturb the participants' work although accuracy

and timeliness should be assured.

3.3 Evaluation index system of seafarers' fatigue

The evaluation index system for seafarers' fatigue can be divided into three layers according to the principle of the AHP. The top layer of these indexes is the goal of the evaluation system, namely evaluating seafarers' fatigue. The second layer is the brief criteria defining the basic factors to achieve the goal of the evaluation system, which includes four subsystems, namely crew-specific factors, management factors, ship-specific factors and environmental factors. The third layer is the detailed criteria which describe the detailed indexes that belong to each brief criterion in the second layer.

Since the hypothesis of the evaluation is that the seafarers are in good health and no significant change has occurred in their family or work, the indexes related to these aspects were removed. Furthermore, the approach of questionnaire[9] survey was used to collect experts' opinions on the selection of factors for the index system. Some of the indexes, such as biological clock, stress, and ingested chemicals, were integrated or removed so as to make it easier to implement the evaluation. Finally, the evaluation index system for seafarers' fatigue was established, including the following factors:

    (a) Crew-specific factors: sleep and rest, working hours, skills and experience

    (b) Management factors: level of manning, frequency of port calls, paperwork requirements

    (c) Ship-specific factors: level of automation, age of ship, accommodation environment

    (d) Environmental factors: weather and sea conditions, traffic density,

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[9] The form of the questionnaire is shown in Appendix A; the results of these questionnaires are shown in Appendix B.

interpersonal relationships

The structure of the evaluation index system for seafarers' fatigue is illustrated by Figure 3.2.
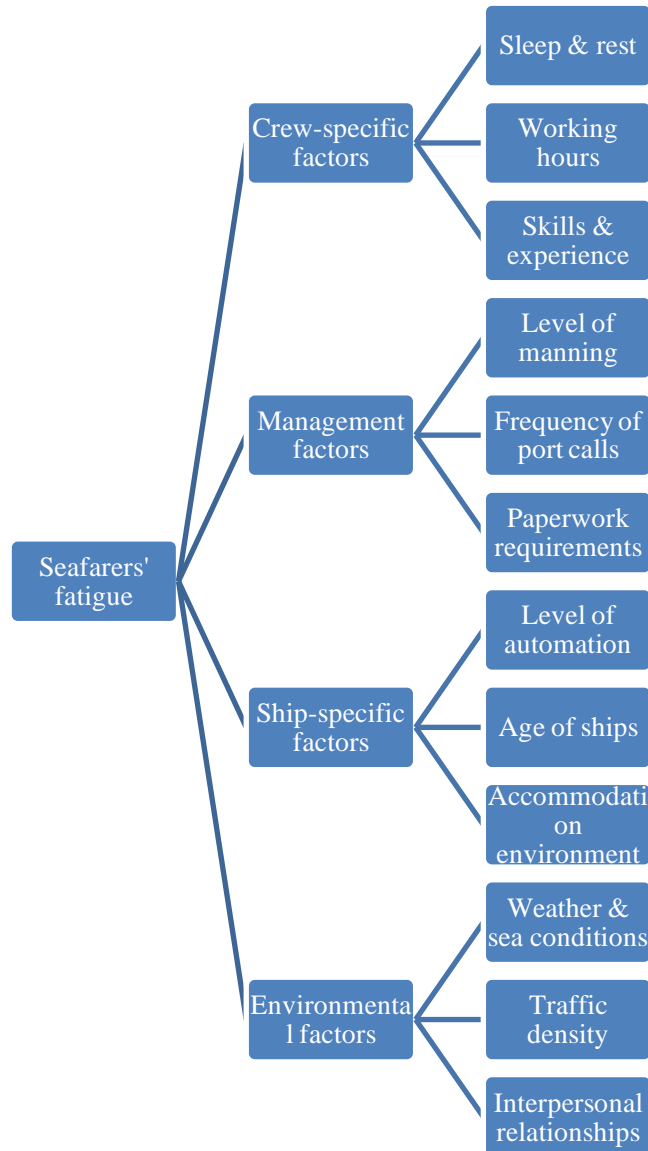
Figure 3.2 The structure of index system of seafarers' fatigue

3.4 Concluding remarks

As a complex issue, fatigue is caused and affected by a combination of risk factors. In this chapter, the contributing factors to fatigue at sea were analyzed and

classified into four categories: crew-specific factors, management factors, ship-specific factors and environmental factors, each of which includes a number of sub-factors. Finally, a three-layer evaluation index system for seafarers' fatigue was finally established following several specific criteria and the principle of the AHP.

Chapter IV Evaluation model of seafarers' fatigue

4.1 Theoretical background of the study

In this paper, the Analytic Hierarchy Process (AHP) will be applied to determine the weight of the indexes. The method of fuzzy comprehensive evaluation will be introduced to set the evaluation model, in consideration of the complexity of the seafaring industry, the ambiguity of fatigue level and the lack of data and information.

4.1.1 The Analytic Hierarchy Process

Developed by Thomas Saaty, the AHP (Saaty, 2008) is one of best known and most widely used multi-criteria decision making tools for complex problems. Both qualitative and quantitative aspects of the problems are considered in the method. Desirable characteristics of such an approach include simplicity, usefulness for both individuals and groups, accommodation of intuition, compromise, and absence of prejudice toward specialized skills or knowledge. The basic procedure to carry out the AHP consists of the following steps:

(a) Structuring the decision hierarchy

The first step of the AHP is to decompose a decision problem into its constituent parts. In its simplest form, the structure comprises a goal of decision at the topmost level, criteria at the intermediate levels, while the lowest level contains a set of

alternatives.

(b) Constructing a set of pair-wise comparison matrixes

For each pair of criteria, the decision maker is required to determine how many times more important one criterion is to another criterion. By making pair-wise comparisons at each level of the hierarchy, participants can develop relative weights to differentiate the importance of the criteria.

To make comparisons, a scale of numbers is needed to indicate the relative importance of the elements. The scale (Saaty, 2008) recommended by Saaty is 1 through 9, with 1 meaning no difference in importance of one criterion in relation to the other and 9 meaning one criterion is extremely more important than the other, with increasing degrees of importance in between. The "reverse" comparisons simply use the reciprocal values in the matrix of comparisons that results (see Table 4.1).

Table 4.1 The scale of absolute numbers (1-9 Scale)

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two factors contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favor one attribute over another
5	Strong Importance	Experience and judgment strongly favor one attribute over another
7	Very Strong Importance	An attribute is strongly favored and its dominance demonstrated in practice
9	Extreme Importance	The evidence favoring one attribute over another is of the highest possible order of affirmation
2,4,6,8	Between the adjacent importance	When compromise is needed
Reciprocals of the above	The "reverse" comparisons of the above comparisons (eg. the result of j to i is the reciprocal of i to j)	

Assume P_1、P_2、$\cdots$、P_n are factors of P level, which are correlated with the factor C_s of level C. The comparison matrix composed of relative priorities of

factors P_i is constructed as follows:

$$A = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & b_{22} & \cdots & b_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix}$$

(c) Calculating the weight of each factor

After the construction of the judgment matrix, the next step is to determine how well "P_i" meets criterion "C_s". First, calculate the product of factors in each row of the judgment matrix using the formula $M_i = \prod_{j=1}^{n} b_{ij}$; and then calculate the $n-th$ root of M_i: $\overline{W}_i = \sqrt[n]{M_i}$; finally the weight of "P_i" to "C_s" can be synthesized using the formula:

$$W_i = \frac{\overline{W}_i}{\sum_{i=1}^{n} \overline{W}_i} \quad (i = 1, 2; \cdot\ n)$$

(d) Consistency inspection

As Saaty described, the method involves redundant comparisons to improve validity recognizing that participants may be uncertain or make poor judgments in some of the comparisons (Saaty, 2008). The multiple comparisons caused by redundancy may lead to numerical inconsistencies. Saaty suggested the error in these measurements is tolerable only when it is of a lower order of magnitude (10%) than the actual measurement itself. The consistency of the comparisons can be checked by the following steps:

- Calculate the largest eigenvalue of the judgment matrix: $\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i}$;

- Calculate the consistency index (CI): $C.I. = \dfrac{\lambda_{\max} - n}{n - 1}$;

- Check the mean random consistency index RI in table 4.2;

- Calculate the Consistency Ratios (CR): $CR = \dfrac{CI}{RI}$.

As long as $CR \leq 0.10$, analysis can proceed.

Table 4.2 the mean random consistency index RI

Rank n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

(e) Obtaining the overall weight of each factor

In this step the overall weight of each element is obtained by combining the option scores with the criterion weights. The extent to which the elements of the lower level satisfy the criteria of an upper level is weighed according to the relative importance of the criteria, which is done by simple weighted summation.

4.1.2 Fuzzy Comprehensive Evaluation

Since the level of risk is a fuzzy concept, the fuzzy mathematics is usually used in the research requiring a quantitative result. The fuzzy comprehensive evaluation refers to the method using fuzzy mathematics to give a scientific appraisal to something with all the influencing factors being considered. The fuzzy comprehensive evaluation consists of sing-level fuzzy comprehensive evaluation and multi-level fuzzy comprehensive evaluation. In the multi-level fuzzy comprehensive evaluation, the second-level indexes are first evaluated comprehensively, then the first-level indexes follow, and finally the evaluation result obtains. The procedure of multi-level fuzzy comprehensive evaluation is as follows:

(a) Building the multi-level set of evaluating indexes

Suppose U is the set of all the first-level factors, which can be expressed as $U = \{u_1, u_2, \cdots, u_n\}$, in which u_i represents the set of all the second-level factors

subject to it. The second-level factors subject to u_i can be expressed as $u_i = \{u_{i1}, u_{i2}, \cdots, u_{im}\}$.

(b) Determining the weight set of indexes

Suppose the weight of the first-level index u_i is w_i, the weight set for fuzzy set U can be expressed as $W = (w_1, w_2, \cdots, w_n)$. Then the weight set of the second-level index u_{ij} is $w_i = (w_{i1}, w_{i2}, \cdots, w_{im})$.

(c) Building the appraisal set

The appraisal set of the risk factors is the set of all the possible evaluation results for the evaluation object. It can be defined as $V = (v_1, v_2, \cdots, v_p)$, in which v_j $(j = 1, 2, \cdots, p)$ represents the possible evaluation result.

(d) Comprehensive evaluation of second-level factors

The construction of membership matrix is an important step to carry out the comprehensive evaluation. After making the criterion of the comment degree to every risk index, experts give a mark to every factor contrasting to the criterion of risk degree, composing the membership vector. Suppose the evaluation is carried on the k_{th} factor u_{ij} of the i_{th} class, and its membership degree subordinated to appraisal set v_j is r_i. Then the membership matrix of u_{ij} can be obtained as

$$r_i = \begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1m} \\ r_{i21} & r_{i22} & \cdots & r_{i2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inm} \end{bmatrix}$$

So the evaluation vector B_i can be calculated

$$B_i = w_i \bullet r_i = \left(w_{i1}, w_{i2}, \cdots, w_{in} \right) \bullet \begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1m} \\ r_{i21} & r_{i22} & \cdots & r_{i2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inm} \end{bmatrix} = \left(b_{i1}, b_{i2}, \cdots, b_{im} \right)$$

(e) Comprehensive evaluation of first-level factors

The single-factor membership matrix of the first-level factors is

$$R = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix} = \begin{bmatrix} w_1 \bullet r_1 \\ w_2 \bullet r_2 \\ \cdots \\ w_n \bullet r_n \end{bmatrix}.$$

The final evaluation vector B can be calculated using the following equation:

$$B = W \bullet R = W \bullet \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_n \end{bmatrix}$$

(f) Defuzzification

In order to get the final evaluation result, the comprehensive matrix should be defuzzified. In this thesis, the final evaluation vector was defuzzified using the weighted average method, which can be achieved by the following formula:

$$V = \frac{\sum\limits_{j=i}^{m} b_j v_j}{\sum\limits_{j=1}^{m} b_j}$$

4.2 The multi-level set of evaluation indexes

The construction of index set is crucial relating to the reasonability and accuracy of the fuzzy comprehensive evaluation. According to the evaluation index system established, the evaluation index sets for seafarers' fatigue are obtained as:

$U = ($crew-specific factors u_1, management factors u_2, ship-specific factors u_3,

environmental factors u_4), in which:

u_1 =(sleep & rest u_{11}, working hours u_{12}, skills & experience u_{13});

u_2 =(level of manning u_{21}, frequency of port calls u_{22}, paperwork requirements u_{23});

u_3 =(level of automation u_{31}, age of ship u_{32}, accommodation environment u_{33});

u_4 =(weather & sea conditions u_{41}, traffic density u_{42}, interpersonal relationships u_{43}).

4.3 The appraisal set

The appraisal set for the risk factors is the set of all the possible evaluation results for the evaluation object. This paper set the level of fatigue into five grades v_1, v_2, v_3, v_4, v_5, namely very low, low, medium, high and very high, represented by -2, -1, 0, 1, 2 respectively. So the appraisal set is obtained as follows:

$$V = \{v_1, v_2, v_3, v_4, v_5\}$$
$$= \{\text{very low, low, medium, high, very high}\}$$
$$= \{-2, -1, 0, 1, 2\}$$

4.4 Construction of membership functions

4.4.1 Membership functions of crew-specific factors

(a) Sleep and rest

It has been confirmed that quality, quantity and duration of sleep are three key

components for a good sleep. A deep and uninterrupted sleep is important for a normal seafarer who wants to have a good performance at work (IMO, 2001). And the quality of sleep during the day is not as high as that during the night. According to the Research of the US Coast Guard, people need 7-8 hours of sleep per 24-hours to perform at their best. In addition, seafarers should have sufficient rest breaks during work as they can also impact the performance and alertness of seafarers.

According to STCW Convention & Codes (2011), all persons who are assigned duties as an officer in charge of a watch or as a rating forming part of a watch shall be provided a minimum of 10 hours of rest in any 24-hour period. The hours of rest may be divided into no more than two periods, one of which shall be at least 6 hours in length. There are similar requirements on hours of work and hours of sleep in regulation 2.3 of MLC, 2006 (2006).

As the factor of sleep and rest has the character of fuzziness which is difficult to be quantified, sleep hours was finally chosen as an indicator to rank the fatigue level caused by the factor of sleep and rest. The evaluation criteria of sleep hours were determined after the literature review and expert inquiry[10], as shown in table 4.3.

Table 4.3 The evaluation criteria of sleep hours (hours/day)

Rank	v_1	v_2	v_3	v_4	v_5
Sleep hours	>7	5.5~7	4.5~5.5	3~4.5	<3

The membership functions of sleep hours can be constructed as follows:

$$f_{v1}(x) = \begin{cases} 1 & x > 7 \\ \dfrac{x-6.25}{7-6.25} & 6.25 \le x < 7 \\ 0 & x \le 6.25 \end{cases} \qquad (4.1)$$

---

[10] The results of the questionnaires concerning the criteria of evaluating factors are shown in Appendix D.

$$f_{v2}(x)=\begin{cases} \dfrac{7-x}{7-6.25} & 6.25 \le x < 7 \\[2mm] \dfrac{x-5}{6.25-5} & 5 \le x \le 6.2 \\[2mm] 0 & x < 5, \text{ or } x \ge 7 \end{cases} \qquad (4.2)$$

$$f_{v3}(x)=\begin{cases} \dfrac{6.25-x}{6.25-5} & 5 \le x < 6.25 \\[2mm] \dfrac{x-3.75}{5-3.75} & 3.75 \le x < 5 \\[2mm] 0 & x < 3.75, \text{ or } x \ge 6.25 \end{cases} \qquad (4.3)$$

$$f_{v4}(x)=\begin{cases} \dfrac{5-x}{5-3.75} & 3.75 \le x < 5 \\[2mm] \dfrac{x-3}{3.75-3} & 3 \le x < 3.75 \\[2mm] 0 & x < 3, \text{ or } x \ge 3.75 \end{cases} \qquad (4.4)$$

$$f_{v5}(x)=\begin{cases} 1 & x < 3 \\[2mm] \dfrac{3.75-x}{3.75-3} & 3 \le x < 3.75 \\[2mm] 0 & x \ge 3.75 \end{cases} \qquad (4.5)$$
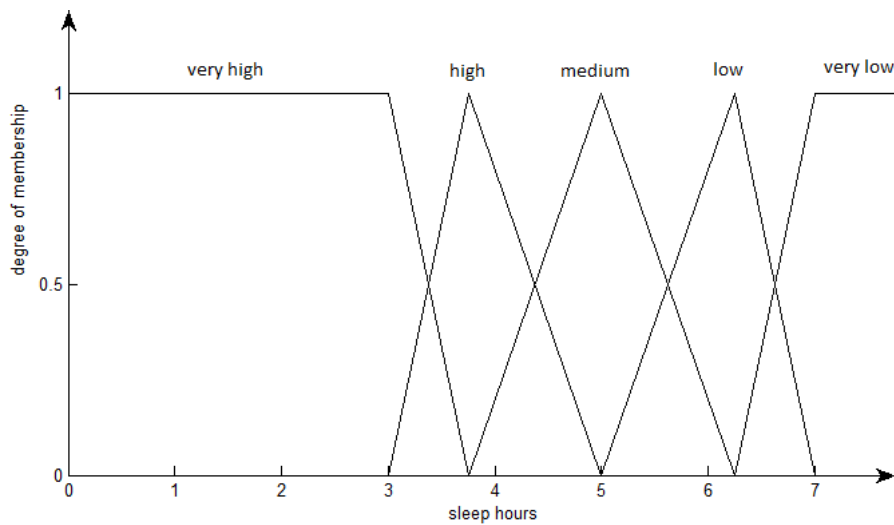

Figure 4.1 Membership degree curves of sleep hours

(b) Working hours

Evidence has shown that working hours are usually used as a yard stick by which fatigue is measured (McCallum, Raby and Rothblum, 1996). The Australian National Transport Commission Fatigue Expert Group (2001) concluded that the limit of daily working time will vary slightly from person to person, but the upper limit is between 12 and 14 hours. The expert group also suggested that the working time should be no more than 70 hours during a seven-day period. According to MLC, 2006, the maximum hours of work shall not exceed 14 hours in any 24-hour period, 72 hours in any seven-day period. The evaluation criteria of working hours were determined after the literature review and expert inquiry, as shown in table 4.4.

Table 4.4 The evaluation criteria of working hours (hours/day)

Rank	v_1	v_2	v_3	v_4	v_5
Working hours	<8	8~10	10~12	12~14	>14

The membership functions of working hours can be constructed as follows:

$$f_{v1}(x) = \begin{cases} 1 & x < 8 \\ \dfrac{9-x}{9-8} & 8 \le x < 9 \\ 0 & x \ge 9 \end{cases} \tag{4.6}$$

$$f_{v2}(x) = \begin{cases} \dfrac{x-8}{9-8} & 8 \le x < 9 \\ \dfrac{11-x}{11-9} & 9 \le x < 11 \\ 0 & x < 9, \text{ or } x \ge 11 \end{cases} \tag{4.7}$$

$$f_{v3}(x) = \begin{cases} \dfrac{x-9}{11-9} & 9 \le x < 11 \\ \dfrac{13-x}{13-11} & 11 \le x < 13 \\ 0 & x < 9, \text{ or } x \ge 13 \end{cases} \tag{4.8}$$

$$f_{v4}(x) = \begin{cases} \dfrac{x-11}{13-11} & 11 \le x < 13 \\ \dfrac{14-x}{14-13} & 13 \le x < 14 \\ 0 & x < 11, \text{ or } x \ge 14 \end{cases} \tag{4.9}$$

$$f_{v5}(x) = \begin{cases} 1 & x \ge 14 \\ \dfrac{x-13}{14-13} & 13 \le x < 14 \\ 0 & x < 13 \end{cases} \tag{4.10}$$
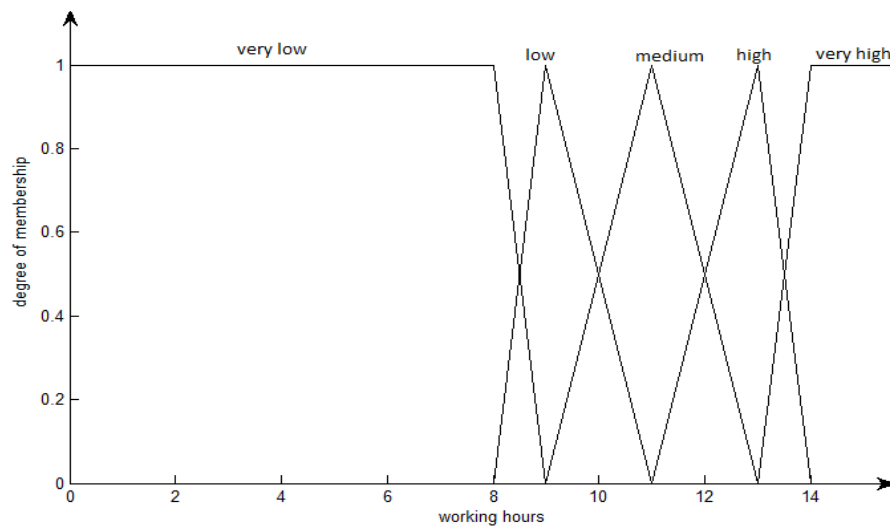
Figure 4.2 Membership degree curves of working hours

(c) Skills & experience

Ship officers' skills and work experience are closely related to their fatigue. Even in the same environment, the extent of fatigue will vary from person to person depending on their skills and experience. Experienced ship officers can handle complicated issues and emergencies better; hence they experience less stress under the same circumstances. Competency certificates are usually used to indicate the seafarers' qualifications. The STCW convention has specific requirements on the qualifications of officers applying competency certificates.

As the ship officers' skills and experience were difficult t quantify, a specialist

marking method was used to rank the level of fatigue caused by this factor. The range of scores is 1-10, with 1 meaning the greatest influence and 10 meaning the least influence, with decreasing degrees of influence in between. The evaluation criteria for the scores of skills & experience can be shown in table 4.5.

Table 4.5 The evaluation criteria for the scores of skills & experience

Rank	v_1	v_2	v_3	v_4	v_5
Score	>9	7~9	5~7	3~5	<3

The membership functions for the scores of skills & experience can be constructed as follows:

$$f_{v1}(x) = \begin{cases} 1 & x > 9 \\ \dfrac{x-8}{9-8} & 8 \leq x < 9 \\ 0 & x \leq 8 \end{cases} \tag{4.11}$$

$$f_{v2}(x) = \begin{cases} \dfrac{9-x}{9-8} & 8 \leq x < 9 \\ \dfrac{x-6}{8-6} & 6 \leq x < 8 \\ 0 & x < 6, \text{ or } x \geq 9 \end{cases} \tag{4.12}$$

$$f_{v3}(x) = \begin{cases} \dfrac{8-x}{8-6} & 6 \leq x < 8 \\ \dfrac{x-4}{6-4} & 4 \leq x < 6 \\ 0 & x < 4, \text{ or } x \geq 8 \end{cases} \tag{4.13}$$

$$f_{v4}(x) = \begin{cases} \dfrac{6-x}{6-4} & 4 \leq x < 6 \\ \dfrac{x-3}{4-3} & 3 \leq x < 4 \\ 0 & x < 3, \text{ or } x \geq 6 \end{cases} \tag{4.14}$$

$$f_{v5}(x) = \begin{cases} 1 & x < 3 \\ \dfrac{4-x}{4-3} & 3 \le x < 4 \\ 0 & x \ge 4 \end{cases} \qquad (4.15)$$
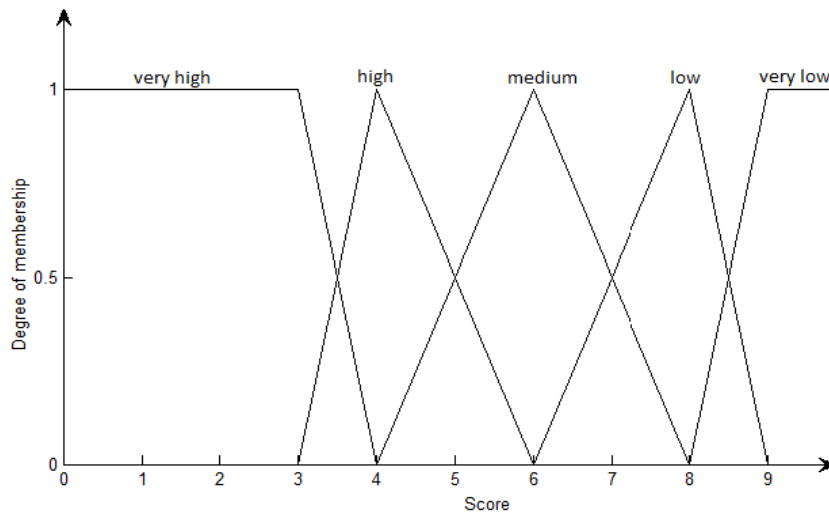
Figure 4.3 Membership degree curves of skill & experience

4.4.2 Membership functions of management factors

(a) Level of manning

It is an ordinary practice to have three officers in each deck and engine department on board a ship, carrying out the normal duties including navigational watches and operations in port. However, the number of crew members has been drastically reduced to the minimum standards mentioned in the Minimum Safe Manning Certificate of a ship due to commercial pressure. As a result, this reality causes a shortage of officers who can conduct a navigational watch properly, increasing the workload and fatigue of current officers. The principles of safe manning, and guidance regarding their application, are laid out in the annexes to IMO Resolution A.890 (21).

As the manning level of ship was difficult to quantify, a specialist marking

method was used to rank the level of fatigue caused by the level of manning, the same method used in the evaluation of skills and experience. The procedure and criteria were the same as those explained before, with evaluation criteria for the scores shown in table 4.5 and the membership functions of the scores shown as formulas 4.11-4.15.

(b) Frequency of port calls

There is a lot of work to do during berthing and departing, such as loading and unloading cargos, supplementing fuel and water, as well as the ever-increasing inspections. Moreover, a high frequency of port turn-around is demanded in pursuit of profit maximization, especially for liner ships. The developed cargo handling facilities also decrease ships' stay in port. When a port turn-around is completed within 24 hours there will be no time for rest before heading back out to sea. As a result, shortened port stays, as well as increased port state and flag state inspections directly cause seafarers' fatigue.

On the basis of a literature review and expert consultancy, time between port calls was chosen as an indicator to rank the fatigue level caused by the frequency of port calls. The evaluation criteria of time between port calls are illustrated in table 4.6.

Table 4.6 The evaluation criteria of time between port calls (weeks)

Rank	v_1	v_2	v_3	v_4	v_5
Time between port calls	>3	2~3	1~2	3/7~1	<3/7

The membership functions of time between port calls can be constructed as follows:

$$f_{v1}(x) = \begin{cases} 1 & x > 3 \\ \dfrac{x-2.5}{3-2.5} & 2.5 \le x < 3 \\ 0 & x \le 2.5 \end{cases} \tag{4.16}$$

$$f_{v2}(x) = \begin{cases} \dfrac{3-x}{3-2.5} & 2.5 \le x < 3 \\ \dfrac{x-1.5}{2.5-1.5} & 1.5 \le x < 2.5 \\ 0 & x < 1.5 \text{ or } x \ge 3 \end{cases} \quad (4.17)$$

$$f_{v3}(x) = \begin{cases} \dfrac{2.5-x}{2.5-1.5} & 1.5 \le x < 2.5 \\ \dfrac{x-5/7}{1.5-5/7} & 5/7 \le x < 1.5 \\ 0 & x < 5/7, \text{ or } x \ge 2.5 \end{cases} \quad (4.18)$$

$$f_{v4}(x) = \begin{cases} \dfrac{1.5-x}{1.5-5/7} & 5/7 \le x < 1.5 \\ \dfrac{x-3/7}{5/7-3/7} & 3/7 \le x < 5/7 \\ 0 & x < 3/7, \text{ or } x \ge 1.5 \end{cases} \quad (4.19)$$

$$f_{v5}(x) = \begin{cases} 1 & x < 3/7 \\ \dfrac{5/7-x}{5/7-3/7} & 3/7 \le x < 5/7 \\ 0 & x \ge 5/7 \end{cases} \quad (4.20)$$
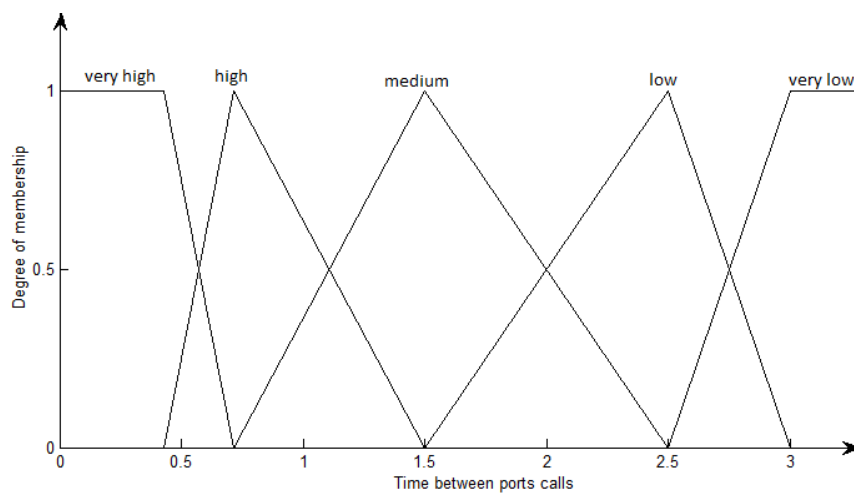

Figure 4.4 Membership degree curves of time between port calls

(c) Paperwork requirements

Technological developments have made the workload on board less intensive, leading to the reduction of manning levels accordingly. However, in contrast with these trends, increasing paperwork, mainly designed to meet the requirements of the ISM Code, Port State Inspections, and ship/shore safety checks, has unwittingly laid higher burdens on the remaining crew. It has become the one of the main complaints of seafarers today that there is too much paperwork. The increasing paperwork can not only sidetrack mariners from their primary responsibilities but also increase their workload, leading to fatigue.

As the factor of paperwork requirements was difficult to quantify, a specialist marking method was used to rank the level of fatigue caused by paperwork requirements, the same method used in the evaluation of skills and experience. The procedure and criteria were the same as those explained before, with evaluation criteria for the scores shown in table 4.5 and the membership functions of the scores shown as formulas 4.11-4.15.

4.4.3 Membership functions of ship-specific factors

(a) Level of automation

New technologies such as ECDIS and AIS have been developed to reduce the navigation workload and are applied onboard ships shortly after their appearance, which has resulted in a high level of automation of new-built ships. It has become necessary to use automation onboard in order to perform complicated tasks or to operate complex machinery. It has reduced the workload of seafarers and relieved their stress, which are the two key factors leading to fatigue. What's more, a high level of automation will probably bring more rest time for the seafarers.

As the factor of level of automation was difficult to quantify, a specialist marking

method was used to rank the level of fatigue caused by the level of automation, the same method used in the evaluation of skills and experience. The procedure and criteria were the same as those explained before, with evaluation criteria for the scores shown in table 4.5 and the membership functions of the scores shown as formulas 4.11-4.15.

(b) Age of ship

The age of vessel is closely related to the seafarers' fatigue because new-built ships have higher maneuvering capabilities than old ships. What's more, the older the ship, the more maintenance it needs. The reliability of the equipment on board also decreases with the increase of ship age. As a result, the ship officers must keep alert all the time when they are on watch, which causes high stress for them, easily leading to fatigue. On the basis of a literature review and expert consultancy, the evaluation criteria of ship age are determined and illustrated in table 4.7.

Table 4.7 The evaluation criteria of age of ship (year)

Rank	v_1	v_2	v_3	v_4	v_5
Age of ship	<3	3~5	5~10	10~18	>18

The membership functions of age of ship can be constructed as follows:

$$f_{v1}(x) = \begin{cases} 1 & x < 3 \\ \dfrac{4-x}{4-3} & 3 \le x < 4 \\ 0 & x \ge 4 \end{cases} \tag{4.21}$$

$$f_{v2}(x) = \begin{cases} \dfrac{x-3}{4-3} & 3 \le x < 4 \\ \dfrac{7.5-x}{7.5-4} & 4 \le x < 7.5 \\ 0 & x < 3, \ \text{or} \ x \ge 7.5 \end{cases} \tag{4.22}$$

$$f_{v3}(x) = \begin{cases} \dfrac{x-4}{7.5-4} & 4 \leq x < 7.5 \\ \dfrac{14-x}{14-7.5} & 7.5 \leq x < 14 \\ 0 & x < 4, \text{ or } x \geq 14 \end{cases} \qquad (4.23)$$

$$f_{v4}(x) = \begin{cases} \dfrac{x-7.5}{14-7.5} & 7.5 \leq x < 14 \\ \dfrac{18-x}{18-14} & 14 \leq x < 18 \\ 0 & x < 7.5, \text{ or } x \geq 18 \end{cases} \qquad (4.24)$$

$$f_{v5}(x) = \begin{cases} 1 & x \geq 18 \\ \dfrac{x-14}{18-14} & 14 \leq x < 18 \\ 0 & x < 14 \end{cases} \qquad (4.25)$$

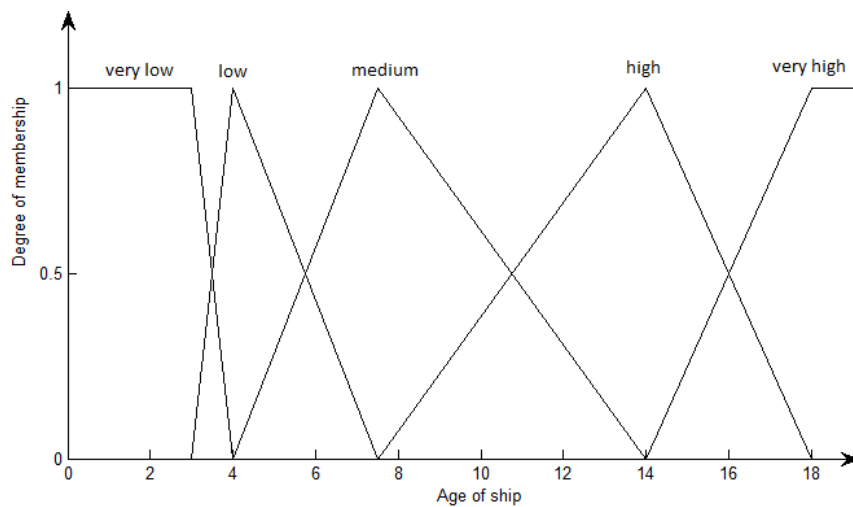Figure 4.5 Membership degree curves of age of ship

(c) Accommodation environment

The physical comfort of accommodation spaces is very important for a good sleep and rest because it might be difficult for the seafarers to fall asleep in a poor accommodation environment. Factors such as heat, vibration, light, noise and ship motion are all crucial factors related to the quality of sleep, the level of physical

stress, and consequently, the level of fatigue.

As the factor of accommodation environment is complicated and was difficult to quantify, a specialist marking method was used to rank the level of fatigue caused by accommodation environment, the same method used in the evaluation of skills and experience. The procedure and criteria were the same as those explained before, with evaluation criteria for the scores shown in table 4.5 and the membership functions of the scores shown as formulas 4.11-4.15.

4.4.4 Membership functions of environmental factors

(a) Weather & sea conditions

Exposure to harsh weather and sea conditions may not only cause seafarers physical discomfort, but also disrupt their sleep and rest, causing or affecting fatigue. Bad weather conditions such as gales and dense fog situations increase the workload of navigation officers and master. Furthermore, seasickness can increase mental and physical fatigue, directly reducing work performance. Factors such as currents and darkness can pose great challenges to seafarers, causing stress and mental fatigue.

As the factor of weather and sea conditions was difficult to quantify, specialist marking method was used to rank the level of fatigue caused by weather and sea conditions, the same method used in the evaluation of skills and experience. The procedure and criteria were the same as those explained before, with evaluation criteria for the scores shown in table 4.5 and the membership functions of the scores shown as formulas 4.11-4.15.

(b) Traffic density

Traffic density is an important index to reflect the traffic situation of a specific water area. High traffic density can increase the risk of collision. Watch conditions are closely related with ship traffic. Ship officers must focus on watch keeping and

keep alert of the surrounding environment in intensive traffic condition. As a result, the officers are in a state of tension and high stress, which can cause mental fatigue.

On the basis of literature review and expert consultancy, the evaluation criteria of traffic density are determined and illustrated in Table 4.8.

Table 4.8 The evaluation criteria of traffic density (vessels/day)

Rank	v_1	v_2	v_3	v_4	v_5
Traffic density	<200	200~400	400~600	600~800	>800

The membership functions of traffic density can be constructed as follows:

$$f_{v1}(x) = \begin{cases} 1 & x < 200 \\ \dfrac{300-x}{300-200} & 200 \le x < 300 \\ 0 & x \ge 300 \end{cases} \tag{4.26}$$

$$f_{v2}(x) = \begin{cases} \dfrac{x-200}{300-200} & 200 \le x < 300 \\ \dfrac{500-x}{500-300} & 300 \le x < 500 \\ 0 & x < 200, \text{ or } x \ge 500 \end{cases} \tag{4.27}$$

$$f_{v3}(x) = \begin{cases} \dfrac{x-300}{500-300} & 300 \le x < 500 \\ \dfrac{700-x}{700-500} & 500 \le x < 700 \\ 0 & x < 300, \text{ or } x \ge 700 \end{cases} \tag{4.28}$$

$$f_{v4}(x) = \begin{cases} \dfrac{x-500}{700-500} & 500 \le x < 700 \\ \dfrac{800-x}{800-700} & 700 \le x < 800 \\ 0 & x < 700, \text{ or } x \ge 800 \end{cases} \tag{4.29}$$

$$f_{v5}(x) = \begin{cases} 1 & x \geq 800 \\ \dfrac{x-700}{800-700} & 700 \leq x < 800 \\ 0 & x < 700 \end{cases} \qquad (4.30)$$
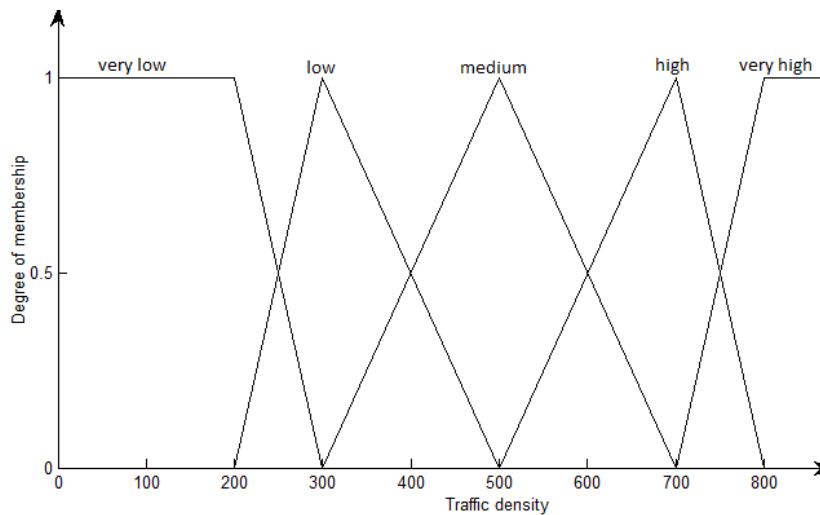
Figure 4.6 Membership degree curves of traffic density

(c) Interpersonal relationships

It is common that seafarers spend between six months and a year working and living away from home. This reality increases a seafarer's psychological fatigue level on board. There is no clear separation between work and recreation when they work on board. What's more, today's seafarers come from various nationalities and backgrounds, which may become a communication barrier between them, leading to loneliness and boredom. All these conditions contribute to the development of mental fatigue.

As the factor of interpersonal relationships was difficult to quantify, a specialist marking method was used to rank the level of fatigue caused by interpersonal relationships, the same method used in the evaluation of skills and experience. The procedure and criteria were the same as those explained before, with evaluation criteria for the scores shown in table 4.5 and the membership functions of the scores shown as formulas 4.11-4.15.

4.5 Weight determination

Questionnaires[11] were distributed to experts and seafarers to seek advice on the relative priority of evaluation factors. The data of these questionnaires were then analyzed and processed, which is shown in appendix D. On the basis of these data, the AHP was applied to determine the weight of these factors.

4.5.1 Weight of first-level factors

As mentioned in the former chapter, the first-level factors include crew-specific factors u_1, management factors u_2, ship-specific factors u_3 and environmental factors u_4. By making pair-wise comparisons, the judgment matrix formed by the relative weights of these factors was determined as follows:

$$A = \begin{bmatrix} 1 & 2 & 2 & 3 \\ 1/2 & 1 & 1 & 2 \\ 1/2 & 1 & 1 & 2 \\ 1/3 & 1/2 & 1/2 & 1 \end{bmatrix}$$

Following the procedure of the AHP, the weight vector of these factors was calculated as:

$$W = (w_1, w_2, w_3, w_4) = (0.4231, 0.2274, 0.2274, 0.1221).$$

The largest eigenvalue $\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nw_i} = 4.0102$.

The consistency ratios $CR = \dfrac{CI}{RI} = 0.0038 < 0.1$, so the result is acceptable.

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[11] The form of the questionnaire is shown in Appendix C; the results of these questionnaires are shown in Appendix D.

Table 4.9 Weight of the first-level factors

Factors	u_1	u_2	u_3	u_4	w_j
u_1	1	2	2	3	0.4231
u_2	1/2	1	1	2	0.2274
u_3	1/2	1	1	2	0.2274
u_4	1/3	1/2	1/2	1	0.1221
λ_{max} =4.0102, CR =0.0038<0.1, the result is correct.					

4.5.2 Weight of second-level factors

(a) Weight of crew-specific factors

As mentioned in the former chapter, crew-specific factors include sleep & rest u_{11}, working hours u_{12}, skills & experience u_{13}. By making pair-wise comparisons, the judgment matrix formed by the relative weight of these factors was determined as follows:

$$A_1 = \begin{bmatrix} 1 & 2 & 4 \\ 1/2 & 1 & 3 \\ 1/4 & 1/3 & 1 \end{bmatrix}.$$

Following the procedure of the AHP, the weight vector of these factors was calculated as:

$$w_1 = (w_{11}, w_{12}, w_{13}) = (0.5584, 0.3196, 0.1220).$$

The largest eigenvalue λ_{max} =3.0182.

Consistency Ratios $CR = \dfrac{CI}{RI}$ =0.0091<0.1, so the result is acceptable.

Table 4.10 Weight of the crew-specific factors

Factors	u_{11}	u_{12}	u_{13}	w_{ij}
u_{11}	1	2	4	0.5584
u_{12}	1/2	1	3	0.3196
u_{13}	1/4	1/3	1	0.1220
λ_{max} =3.0182, CR=0.0091<0.1, the result is correct.				

(b) Weight of management factors

As mentioned before, management factors include level of manning u_{21}, frequency of port calls u_{22}, and paperwork requirement u_{23}. By making pair-wise comparisons, the judgment matrix formed by the relative weight of these factors was determined as follows:

$$A_2 = \begin{bmatrix} 1 & 2 & 3 \\ 1/2 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{bmatrix}.$$

Following the procedure of the AHP, the weight vector of these factors was calculated as:

$$w_2 = (w_{21}, w_{22}, w_{23}) = (0.5396, 0.2970, 0.1634).$$

The largest eigenvalue λ_{max} =3.0093.

Consistency Ratios $CR = \dfrac{CI}{RI}$ =0.0080<0.1, so the result is acceptable.

Table 4.11 Weight of management factors

Factors	u_{21}	u_{22}	u_{23}	w_{ij}
u_{21}	1	2	3	0.5396
u_{22}	1/2	1	2	0.2970

u_{23}	1/3	1/2	1	0.1634
λ_{max} =3.0093, CR =0.0080<0.1, the result is correct.				

(c) Weight of ship-specific factors

As mentioned above, ship-specific factors include level of automation u_{31}, age of ship u_{32}, and accommodation environment u_{33}. By making pair-wise comparisons, the judgment matrix formed by the relative weight of these factors was determined as follows:

$$A_3 = \begin{bmatrix} 1 & 2 & 1 \\ 1/2 & 1 & 1/2 \\ 1 & 2 & 1 \end{bmatrix}.$$

Following the procedure of the AHP, the weight vector of these factors was calculated as:

$$w_3 = (w_{31}, w_{32}, w_{33}) = (0.4, 0.2, 0.4).$$

The largest eigenvalue λ_{max} =3.0.

Consistency Ratios $CR = \dfrac{CI}{RI} = 0.0 < 0.1$, so the result is acceptable.

Table 4.12 Weight of ship-specific factors

Factors	u_{31}	u_{32}	u_{33}	w_{ij}
u_{31}	1	2	1	0.4
u_{32}	1/2	1	1/2	0.2
u_{33}	1	2	1	0.4
λ_{max} =3.0, CR =0.0<0.1, the result is correct.				

(d) Weight of environmental factors

As mentioned in the last chapter, environmental factors include weather & sea

conditions u_{41}, traffic density u_{42}, and interpersonal relationships u_{43}. By making pair-wise comparisons, the judgment matrix formed by the relative weight of these factors was determined as follows:

$$A_4 = \begin{bmatrix} 1 & 2 & 3 \\ 1/2 & 1 & 2 \\ 1/3 & 1/2 & 1 \end{bmatrix}.$$

Following the procedure of the AHP, the weight vector of these factors was calculated as:

$$W_4 = (w_{41}, w_{42}, w_{43}) = (0.5396, 0.2970, 0.1634).$$

The largest eigenvalue $\lambda_{\max} = 3.0093$.

Consistency Ratios $CR = \dfrac{CI}{RI} = 0.0080 < 0.1$, so the result is acceptable.

Table 4.13 Weight of environmental factors

Factors	u_{41}	u_{42}	u_{43}	w_{ij}
u_{41}	1	2	3	0.5396
u_{42}	1/2	1	2	0.2970
u_{43}	1/2	1/2	1	0.1634
$\lambda_{\max} = 3.0093$, $CR = 0.0080 < 0.1$, the result is correct.				

4.6 Evaluation model of seafarers' fatigue

In this paper, a two-level fuzzy comprehensive evaluation method was used to assess seafarers' fatigue. The evaluation model of each level was constructed as follows.

4.6.1 Evaluation of the second-level factors

The second-level factors include four factors, each has three sub-factors. The comprehensive evaluation matrix of crew-specific factors can be obtained as:

$$r_1 = \begin{bmatrix} r_{111} & r_{112} & r_{113} & r_{114} & r_{115} \\ r_{121} & r_{122} & r_{123} & r_{124} & r_{125} \\ r_{131} & r_{132} & r_{133} & r_{134} & r_{135} \end{bmatrix}.$$

So the evaluation vector for crew-specific factors can be obtained as:

$$B_1 = W_1 \bullet r_1 = (w_{11}, w_{12}, w_{13}) \bullet \begin{bmatrix} r_{111} & r_{112} & r_{113} & r_{114} & r_{115} \\ r_{121} & r_{122} & r_{123} & r_{124} & r_{125} \\ r_{131} & r_{132} & r_{133} & r_{134} & r_{135} \end{bmatrix}.$$

Similarly, the evaluation vectors of management factors, ship-specific factors and environmental factors can be obtained as B_2, B_3 and B_4 respectively.

4.6.2 Comprehensive evaluation of first-level factors

The final evaluation vector of seafarers' fatigue can be calculated using the following equation:

$$B = W \bullet R = (W_1, W_2, W_3, W_4) \bullet \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix}.$$

The level of fatigue degree V can be obtained after the defuzzification of the final evaluation vector using weighted average method.

4.7 Case study

4.7.1 Brief introduction of the case

In this case, the fuzzy comprehensive evaluation model was applied to assess the

fatigue level of a ship officer who was randomly selected. The ship officer was physically and mentally healthy and worked as the third officer onboard a bulk carrier of 10,000 GT. The ship was in the short sea and coastal industry along the China coast, carrying coal/grain on board.

4.7.2 Evaluation of the officer's fatigue

(a) Crew-specific factors

The ship had left Shanghai Port two days prior and was expected to arrive at Dalian Port in three days' time. In the three days, the third officer worked 12 hours on average and slept 6 hours. The quality of sleep was good and there was no interruption to his sleep. The officer had worked as a third officer for 10 months, so his skills and experience was scored at 6.5. The membership matrix of these factors can be obtained by the formulas mentioned before.

$$r_1 = \begin{bmatrix} 0 & 0.8 & 0.2 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 \\ 0 & 0.25 & 0.75 & 0 & 0 \end{bmatrix}$$

So the evaluation vector for crew-specific factors can be obtained as

$$B_1 = W_1 \bullet r_1 = (0.5584, 0.3196, 0.1220) \bullet \begin{bmatrix} 0 & 0.8 & 0.2 & 0 & 0 \\ 0 & 0 & 0.5 & 0.5 & 0 \\ 0 & 0.25 & 0.75 & 0 & 0 \end{bmatrix}$$

$$= (0, 0.4772, 0.3630, 0.1598, 0)$$

(b) Management factors

Since the shipping market was in depression, the ship was at the minimum manning level in order to cut down expenses. As a result, there were insufficient officers to carry out the normal duties. The level of manning was scored 4.5. As the ship was operated in the coastal industry along China's coast, the time between port calls was 6 days on average. The paperwork and inspections were not excessive for a

ship engaged in domestic business, so the score of paperwork was 7. The membership matrix of these factors can be obtained by the formulas mentioned before.

$$r_2 = \begin{bmatrix} 0 & 0 & 0.25 & 0.75 & 0 \\ 0 & 0 & 0.18 & 0.82 & 0 \\ 0 & 0.5 & 0.5 & 0 & 0 \end{bmatrix}$$

So the evaluation vector for management factors can be obtained as:

$$B_2 = W_2 \bullet r_2 = (0.5396, 0.2970, 0.1634) \bullet \begin{bmatrix} 0 & 0 & 0.25 & 0.75 & 0 \\ 0 & 0 & 0.18 & 0.82 & 0 \\ 0 & 0.5 & 0.5 & 0 & 0 \end{bmatrix}$$

$$= (0, 0.0817, 0.2701, 0.6482, 0)$$

(c) Ship-specific factors

The ship was built in 2006, so the equipment on board was modern and in good condition. As the level of automation was high, the level of automation was scored 8. The room of the third officer was a comfortable sound-proof room with air conditioning, so the accommodation environment was scored 7. The membership matrix of these factors can be obtained as follows.

$$r_3 = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0.43 & 0.57 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0 & 0 \end{bmatrix}$$

So the evaluation vector for ship-specific factors can be obtained as:

$$B_3 = W_3 \bullet r_3 = (0.4, 0.2, 0.4) \bullet \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0.43 & 0.57 & 0 & 0 \\ 0 & 0.5 & 0.5 & 0 & 0 \end{bmatrix}$$

$$= (0, 0.6860, 0.3140, 0, 0)$$

(d) Environmental factors

The weather and sea conditions in the last three days were fine, so the factor of the weather and sea conditions was scored 6. The traffic density on the route from Shanghai to Dalian was about 500 vessels per day (small fishing vessels excluded).

The relationship of the officer with other crew members was fine, which can be scored as 6.5. The membership matrix of these factors can be obtained by the formulas mentioned before.

$$r_4 = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0.75 & 0.25 & 0 \\ 0 & 0.25 & 0.75 & 0 & 0 \end{bmatrix}$$

So the evaluation vector for environmental factors can be obtained as

$$B_4 = W_4 \bullet r_4 = (0.5396, 0.2970, 0.1634) \bullet \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0.75 & 0.25 & 0 \\ 0 & 0.25 & 0.75 & 0 & 0 \end{bmatrix}$$

$$= (0, 0.0408, 0.8849, 0.0742, 0)$$

(e) Level of fatigue

The membership matrix of first-level factors can be obtained as:

$$R = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{bmatrix} = \begin{bmatrix} 0 & 0.4772 & 0.3630 & 0.1598 & 0 \\ 0 & 0.0817 & 0.2701 & 0.6482 & 0 \\ 0 & 0.6860 & 0.3140 & 0 & 0 \\ 0 & 0.0408 & 0.8849 & 0.0742 & 0 \end{bmatrix}$$

The final evaluation vector of seafarers' fatigue can be calculated:

$$B = W \bullet R = (0.4231, 0.2274, 0.2274, 0.1221) \bullet \begin{bmatrix} 0 & 0.4772 & 0.3630 & 0.1598 & 0 \\ 0 & 0.0817 & 0.2701 & 0.6482 & 0 \\ 0 & 0.6860 & 0.3140 & 0 & 0 \\ 0 & 0.0408 & 0.8849 & 0.0742 & 0 \end{bmatrix}$$

$$= (0, 0.3815, 0.3945, 0.2240, 0)$$

The level of fatigue $V = \dfrac{\sum\limits_{j=i}^{m} b_j v_j}{\sum\limits_{j=1}^{m} b_j} = -0.1575$. According to the appraisal set $V = $

{very low, low, medium, high, very high} $= \{-2, -1, 0, 1, 2\}$. The final result falls into

the interval [-1, 0], which means that the third officer's fatigue degree is between the level of low and medium, much closer to the level of medium.

4.7.3 Validation of the evaluation result

The seafarer's fatigue level was also predicted using MARTHA[12], a prototype maritime fatigue prediction tool developed by the Horizon Project. The prediction result was compared with the evaluation result, which indicated that both methods had similar results. The evaluated fatigue level was close to the level of medium, while the predicted fatigue level was 42%, which was also close to the medium degree. The comparison clearly reveals that the result of the evaluation is acceptable.

4.8 Concluding remarks

The AHP is a useful structured technique for discriminating between competing options in the light of a range of objectives to be met. Fuzzy comprehensive evaluation method is a comprehensive assessment method that applies fuzzy mathematical principles to evaluate things and phenomenon affected by a variety of factors. This chapter first introduced the theoretical background of the AHP and Fuzzy Comprehensive Evaluation. The set of evaluating indexes and the appraisal set for seafarers' fatigue were established before the construction of membership functions of these evaluating factors. The weight of these factors was obtained following the procedure of the AHP. The two-level fuzzy comprehensive evaluation model for seafarers' fatigue was established. Finally the model was applied to evaluate the fatigue level of a third officer who was working onboard a ship in the coastal industry along China's Coast. The evaluation result indicates that the model is suitable for the evaluation of seafarers' fatigue.

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[12] For more details, please visit: http://www.warsashacademy.co.uk/research/horizon/martha.aspx

Chapter V   Recommendations on fatigue's mitigation

Fatigue is caused and affected by a combination of risk factors. It is clearly revealed from the evaluation that a number of measures need to be adopted to prevent or manage fatigue from the perspectives of maritime administrations and organizations, shipping companies and seafarers.

5.1 Recommendations for maritime administrations and organizations

(a) Review of working schedules

Prolonged working hours are a feature of the operational regime onboard that differs from other industries. The unique aspect of the regime is considered as an important element in generating fatigue and especially stress among seafarers (Parker, et al, 1997). Regarding this issue, it is recommended that maritime organizations undertake a complete review of traditional work patterns to minimize the impact of these factors on seafarers' fatigue levels.

In addition, the implementation of regulations concerning the duration of rest periods aboard ships should be examined strictly. A regular review of these international conventions is also recommended to be carried out. The essential information regarding the examination of sleep patterns can be obtained by the analysis of sleep data and the assessment of sleep quality in general (Parker, et al, 1997).

(b) Supervision of the working hours

Since working hours are a crucial fatigue factor for seafarers, it is important to know how long seafarers are working in terms of evaluating their current fatigue levels. A clear separation between work and rest can relieve seafarers' fatigue. It is revealed in many studies that proper supervision of working hours will be helpful for the seafarers to make such separations (IMO, 2001). However, the current method for recording and auditing working hours is not effective. As a result, the current method should be reviewed and new methods should be developed.

(c) More robust approaches to manning levels

Since it is possible to gain economic advantage by operating with minimum manning levels, such a situation should be prevented by addressing manning levels in a more realistic and robust regulation. Furthermore, it is necessary to state that manning must be at more than the minimum level so as to safely operate a vessel. The manning of a vessel may be sufficient for a passage of open sailing; however, the same vessel may have insufficient crew when carrying out tasks such as maintenance, port turn-arounds and ship inspections.

(d) Enforcing existing regulations and guidelines

The existing regulations and guidelines with mandatory provisions should be enforced to enhance the prevention and management of fatigue at sea. Supplemented measures such as appropriate training and more guidance regarding avoidance of fatigue and optimum working conditions should be taken to ensure the implement of these existing regulations.

Other measures for maritime administrations to mitigate fatigue include fewer administrative tasks, fewer inspections in the harbor, and better co-ordination of inspections.

5.2 Recommendations for shipping companies

(a) Training

Every new technology designed to increase navigational safety has brought new skills and new compulsory training such as ECDIS and BRM training. In light of the introduction of these technological aids in the shipping industry, it is also of great importance to conduct appropriate training and retraining for seafarers in combating fatigue. Training concerning manning levels and management issues should also be carried out for managerial staff of shipping companies (Parker, et al, 1997; IMO, 2001). What's more, lessons can be learned from the best practices of other transport sectors, such as fatigue awareness training and fatigue management training.

(b) Improvement of shipboard conditions

Improvements to shipboard conditions should be made in order to minimize their negative effects upon seafarers. Contributing factors related to seafarers' work and rest environment such as heating, ventilation and air-conditioning should be maintained on schedule to reduce their effects on seafarers' fatigue. Sources of unusual noise should be detected and solved at the first possible opportunity. Moreover, good illumination and music in the working places may be useful for the relief of stress. Within the seafarers' accommodation, steps should been taken to ensure that the highest possible standards of comfort are provided.

(c) Establishment of safety culture onboard ships

More efforts should be made to convince seafarers that it should be a conscious decision to comply with the international maritime regulations regarding safety, with the philosophy that prevention is better than cure. It is also necessary to increase team awareness because it can reduce both psychological and physical fatigue on board. In addition, it is important to establish shipboard practices for dealing with fatigue incidents. Lessons from past fatigue-induced accidents should become a part

of safety meetings onboard ships. What's more, an open communication environment should be established because systematic reporting of fatigue cases by the seafarers can assist greatly in a comprehensive assessment of the problem (Bhatt, 2006).

(d) Optimization of the organization of work

Onboard management techniques especially those recommended by the IMO and the ILO should be utilized to ensure that shipboard work and rest periods can be scheduled in a more efficient manner. In some cases, a number of tasks can be mixed to prevent the appearance of monotony. Work that requires high physical or mental demands can be combined with relatively undemanding work so as to reduce work intensity. In addition, drills can be arranged in a manner that leads to the lowest possibility of disturbing rest periods. It is also important to find new working strategies to avoid the occurrence of overtime.

5.3 Recommendations for seafarers

(a) Sleep

Sleep is considered as the most effective strategy to fight fatigue. Sleep loss and sleepiness can impair a person's performance in the physical, emotional and mental aspects. So it is very important for seafarers to sleep well on board. Some suggestions on developing good sleep habits are listed below:

- develop and follow a pre-sleep routine to promote sleep at bedtime, e.g. taking a warm shower before going to bed;
- satisfy any other physiological needs before going to sleep, e.g. visiting the toilet before trying to sleep;
- avoid alcohol and caffeine prior to sleep;
- and exercise some techniques to relax the body before going to sleep, e.g. meditation and yoga.

(b) Rest breaks & strategic napping

Rest breaks, apart from sleep, are indispensable as a physical requirement for the maintenance of performance in a good state. They can be provided in the form of breaks or changes in activities. What's more, strategic napping is also a good choice for a seafarer to recover his strength and stamina. As a result, it is recommended that seafarers should have sufficient breaks or strategic napping as long as the situation allows.

(c) Lifestyle behaviors

Traditionally, it is well known that physical exercise is an important technique to relieve stress. So some exercise models should be developed onboard ships and seafarers should be motivated to participate in exercises. In the same way, it is also a good approach to offer more time for relaxation and appropriate programs concerning the management of fatigue.

Nutrition onboard is always a crucial factor contributing to health and fatigue. Eating regularly, well-balanced meals and drinking a sufficient amount of water are helpful for the mitigation of fatigue. Reductions in the consumption of high-fat and fried foods are also important in diminishing fatigue. What's more, the consumption of alcohol and tobacco should be strictly restricted in the seafaring community so as to alleviate the fatigue issue aboard ship.

5.4 Concluding remarks

Fatigue at sea is a complex problem affected by a list of factors. So it can be managed and prevented from different aspects. In this chapter some suggestions were given to maritime organizations, shipping companies and seafarers respectively. The working schedules and sleep patterns should be reviewed carefully. Existing regulations and guidelines should be enforced while new rules should be brought into

force for reducing fatigue of seafarers. Efforts should be made so that officers will need less time for paper work. New training programs pertaining to new technologies as well as fatigue management should be developed. Workload management should be applied on board to optimize the organization of work. A Safety culture should be established on board and social facilities for seafarers at port should be developed. Navigation bridges and accommodation places should be designed taking into account ergonomic aspects. For the seafarers, proper sleep habits should be developed to ensure the quality of sleep. Healthy lifestyle behaviors should also be established so as to effectively manage fatigue.

Chapter VI　Overall Conclusions

6.1 Conclusions of the research

Seafarers' fatigue has become a global concern across the shipping industry. This dissertation tried to find a solution for fatigue evaluation and mitigation with the application of the AHP and fuzzy comprehensive evaluation method, based on the analysis of all the main components of fatigue.

Fatigue is a complicated issue which is caused and affected by many factors. In light of these indications, a comprehensive understanding of fatigue was achieved by examining its background, its definition and its effects on seafarers. Fatigue can be generally defined as a temporary loss of strength and energy resulting from hard physical or mental work. Fatigue can impair the seafarers' performance at work, diminish their alertness, and affect their problem-solving and decision-making abilities, leading to errors and subsequent maritime casualties.

Naturally, an examination of the prevalence of fatigue at sea can reveal fatigue's role in the life and work of seafarers, while the examination of maritime disasters related to fatigue can reveal fatigue's role in accidents. With regard to this issue, relevant statistical data and accident cases related to fatigue were collected and analyzed, which indicated that fatigue played a crucial role in maritime casualties.

Furthermore, the contributing factors to seafarers' fatigue were analyzed and classified as follows: crew-specific factors, management factors, ship-specific factors

and environmental factors. These essential elements are of great importance in dealing with fatigue issues, especially for the establishment of an evaluation index system and the development of evaluation models. In this paper, a three-layer evaluation index system was established, covering most of the risk factors.

As the core part of the dissertation, the establishment of an evaluation model was the final objective of the dissertation. In the process of establishing the model, the AHP was applied to determine the weight of the indexes and fuzzy comprehensive evaluation method was applied to construct the model and assess the level of fatigue. The model was then applied to a case study, in which the fatigue level of a third officer aboard a coastal vessel was assessed.

With respect to the mitigation of fatigue, a number of recommendations were given to maritime organizations, shipping companies and seafarers respectively, including, but not limited to, comprehensive reviews of work schedules and sleeping issues, enforcement of related international regulations and guidelines, mitigation of environmental hardships, establishment of safety culture onboard ships, necessary training and retraining for seafarers and managerial staff and development of proper sleep habits.

In the whole, fatigue is a very important issue at the present time to the whole maritime community due to its crucial role in maritime casualties which pose a great risk to human life and property, as well as the marine environment. The fatigue level of seafarers can be assessed using fuzzy comprehensive evaluation method. A list of countermeasures can be taken to manage and reduce the effects of fatigue.

6.2 Limitations of the research

Although extensive work has been done in the dissertation seeking resolutions for the mitigation of fatigue among seafarers, there are some limitations of the research.

Firstly, the evaluation model was not perfect as the indexes selected were not enough to cover every aspect of fatigue. Secondly, some of the criteria of the evaluation indexes were determined based on expert inquiry, which can lead to subjectivity to some extent. Thirdly, the data for the seafarer being evaluated was not accurate enough as some of them were acquired by interview and could not be quantified. Last but not least, the method for the measurement of fatigue needs to be improved so as to better deal with the subjective indexes. The evaluation model should be adjusted as the fatigue level caused by the same factors may vary from person to person.

Obviously, there are many things to do in the future for the management and mitigation of fatigue among seafarers. Lessons can be learned from other transport industries and examples of best practice can be applied in an effective way to the maritime sector. There is a long history of research on fatigue of drivers in road transport, resulting in a mature system for the measurement and evaluation of fatigue, which can be applied in the maritime domain. What's more, a tool that is universally applicable for the assessment of the fatigue levels of seafarers should be developed in the future so as to make the work of fatigue evaluation easier and more accurate.

References

Akerstedt, T. and Haraldsson, P.O. (2001). International consensus meeting on fatigue and the risk of traffic accidents. The significant of fatigue for transportation safety is underestimated. *Läkartidningen, 98(25), 3014-7.*

Allen, P., Wadsworth, E. and Smith, A. (2006). The relationship between recorded hours of work and fatigue in seafarers. In P.D. Bust (Eds), *Contemporary Ergonomics 2006* (pp. 546-548). London: Taylor and Francis.

Allen, P.H., Wadsworth, E.J. and Smith, A.P. (2008). Seafarers' fatigue: a review of the recent literature. *International Maritime Health, 59, 81-92.*

Amagasa, T., et al. (2005). Karojisatsu in Japan: Characteristics of 22 cases of Work-Related Suicide. *Journal of Occupational Health, 47,157-164.*

Andrea, H., Kant I.J., Beurskens, AJHM., Metsemakers, JFM and van Schayck, C.P. (2003). Associations between fatigue attributions and fatigue, health, and psychosocial work characteristics: a study among employees visiting a physician with fatigue. *Occupational and Environmental Medicine, 60, i99-i104.*

Australian National Transport Fatigue Expert Group. (2001). *Options for a regulatory approach to fatigue in drivers of heavy vehicles in Australia and New Zealand.* Retrieved 3 May, 2012 from:
http://www.ntc.gov.au/filemedia/Reports/FatigueExpertGroupRepFeb2001.pdf

Battelle Memorial Institute. (1998). *An Overview of the Scientific Literature Concerning Fatigue, Sleep and the Circadian Cycle.* Retrieved May 5, 2012 from:
http://www.vcockpit.de/fileadmin/dokumente/presse/2003/BatelleReport1998.pdf

Belyavin, A.J. and Spencer, M.B. (2004). Modelling performance and alertness: The QinetiQ approach. *Aviation, Space and Environmental Medicine, 75, 93-103.*

Bensing, J.M., Hulsman, R.L. and Schreurs, K.M.G. 1999. Gender differences in fatigue: biopsychosocial factors relating to fatigue. *Medical Care, 37(10), 1078-1083.*

Bhatt, L. (2006, March). Accidents and fatigue. *Seaways, 3*.

Bonnet, M.H. and Arand, D.L. (1995). We are chronically sleep deprived. *Sleep, 18, 908-911.*

Brown, I.D. (1989). *Study into hours of work, fatigue and safety at sea*. Medical Research Council: Cambridge.

Brown, I.D. (1997). Prospects for technological countermeasures against driver fatigue. *Accident Analysis and Prevention, 29(4), 525-531.*

Buck, L. and Lamonde, F. (1993). Critical incidents and fatigue among locomotive engineers. *Safety Science, 16(1), 1-18.*

Bültman, U., Kant, I.J., van den Brandt, P.A. & Kasl, S.V. (2002). Psychosocial work characteristics as risk factors for the onset of fatigue and psychological distress: prospective results from the Maastricht Cohort Study. *Psychological Medicine, 32(2), 333-345.*

Cameron, C. (1971). Fatgiue, problems in modern industry. *Ergonomics, 14(6), 713-720.*

Charlton, SG. and Baas, PH. (2001). Fatigue, work-rest cycles, and psychomotor performance of New Zealand truck drivers. *New Zealand Journal of Psychology, 30, 32-39.*

Chen MK. (1986). The epidemiology of self-perceived fatigue among adults. *Prev Med, 15(1)*, 74-81.

Collins, A., Mathews, V., and McNamara, R. (2000). *Fatigue, health and injury among seafarers & workers on offshore installations: A review.* Cardiff University Seafarers International Research Centre/Centre for Occupational & Health Psychology.

Connor, J., Whitlock, G., Norton, R. and Jackson, R. (2001). The role of driver sleepiness in car crashes: A systematic review of epidemiological studies. *Accident Analysis and Prevention, 33, 31-41.*

Crawford, A. (1961). Fatigue and driving. *Ergonomics, 4(2), 143-54.*

David A., Pelosi A., McDonald E., Stephens D., Ledger D., Rathbone R. & Mann A. (1990). Tired, weak, or in need of rest: fatigue among general practice attenders. *The British Medical Journal, 301, 1199-1202.*

Der-Shin Ke. (2012). Overwork, Stroke, and Karoshi-death from Overwork. *Acta Neurol Taiwan 2012, 21, 54-59.*

Det Norske Veritas. (1999). *Great Barrier Reef Pilotage Fatigue Risk Assesment for AMSA.* Retrieved April 8, 2012 from: http://www.docstoc.com/docs/37213638/Great-Barrier-Reef-Pilotage-Fatigue-Risk-Assessment

Dinges, DF. and Mallis, MM. (1998). Managing fatigue by drowsiness detection: Can technological promises be realized? In Hartley LR (Eds), *Managing fatigue in transportation.* Oxford: Elsevier.

Ellis, N., Allen, P., and Burke, A. (2003). The influence of noise and motion on sleep, mood and performance of seafarers. In P.T. McCabe (Eds), *Contemporary Ergonomics 2003* (pp. 137-142). United Kingdom: Taylor & Francis

Fatigue: IMO guidance, mitigation and management. 2006, March. *Seaways, 7-9.*

Folkard, S., Lombardi, DA and Tucker, PT. (2005). Shiftwork: safety, sleepiness and sleep. *Industrial Health, 43, 20-23.*

Foo, S.C., How, J., Siew, M.G., Wong, T.M., Vijayan, A. and Kanapathy, R. (1994). Effects of sleep deprivation on naval seamen: II. Short recovery sleep on performance. *Annals of the Academy of Medicine, Singapore, 23(5), 676-679.*

Gander, PH., Graeber, RC., Connell, LJ., Gregory, KB., Miller, DL. and Rosekind, MR. (1998a). Flight crew fatigue I: objectives and methods. *Aviation, space, and environmental medicine, 69(9 suppl), B1-7.*

Gander, PH., Gregory., KB, Mille r, DL., Graeber, RC., Connell, LJ. and Rosekind, MR. (1998b). Flight crew fatigue V: long-haul air transport operation. *Aviation, space, and environmental medicine, 69(9 suppl), B37-48.*

Gander, PH., Rosekind, MR., and Gregory, KB. (1998c). Flight crew fatigue VI: a synthesis. *Aviation, space, and environmental medicine, 69(9 suppl), B49-60.*

Gander, P. (2005). *A review of fatigue management in the maritime sector*. Wellington: Massey University Sleep/Wake research centre.

gCaptain. (April 15, 2010). Shen Neng 1: Fatigue, Inexperience, Wrong chart. Retrieved 12 May, 2012 from: http://gcaptain.com/shen-neng-1-fatigue-inexperience-wrong-chart/

Goodwin, P. (1996). Empirical evidence on induced traffic. *Transportation, 23, 35-54.*

Grandjean, EP., Wotzka, G., Schaad, R. and Gilgen, A. (1971). Fatigue and stress in air traffic controllers. *Ergonomics, 14(1), 159-165*.

Grant, JS. (1971). Concepts of fatigue and vigilance in relation to railway operation. *Ergonomics, 14(1), 111-118.*

Hakkanen, H. and Summala, H. (2000). Sleepiness at work among commercial truck drivers. *Sleep, 23, 49-57.*

Hamelin, P. (1987). Lorry drivers' time habits in work and their involvement in traffic accidents. *Ergonomics, 30, 1323-1333*.

Haraldsson, PO., Carenfeldt, C., Diedrichsen, F., Nygren, A. and Tingvall, C. (1990). *Journal for Otorhinolarngology and its related specialties, 52, 57-62*.

Houtman, I., Miedema, M., Jettinghoff, K., Starren, A, Heinrich, J., Gort, J., Wulder, J. & Wubbolts, S. (2005, December 28). *Fatigue in the shipping industry*. Hoofddorp: Netherlands Organization for Applied Scientific Research TNO.

How, J.M., Foo, S.C., Low, E., Wong, T.M., Vijayan, A., Siew, M.G. and Kanapathy, R. (1994). Effects of sleep deprivation on performance of naval seamen: I. Total sleep deprivation on performance. *Annals of the Academy of Medicine, Singapore, 23(5), 669-675.*

Huibers, M., Bleijenberg, G., van Amelsvoort, L., Beurskens, A., van Schayck, C., Bazelmans, E and Knottnerus, J. (2004). Predictors of outcome in fatigue employees on sick leave. Results from a randomised trial. *Journal Psychosomatic Research, 57, 443-449*.

International Maritime Organization. (1999, June 6). *The role of the human element*

(MSC/Circ. 813/MEPC/Circ.330). London: Author.

International Maritime Organization. (2001, June 12). *Guidance on Fatigue Mitigation and Management* (MSC/Circ.1014). London: Author.

International Maritime Organization. (2011). *Maritime Safety*. Retrieved July 5, 2012 from International Maritime Organization website: http://www.imo.org/OurWork/Safety/Pages/Default.aspx

International Transport Workers' Federation. (1998). *Seafarer fatigue: Wake up to the dangers*. London: Author.

Iwasaki, K., Takahashi, M. and Nakata. A. (2006). Health problems due to long working hours in Japan: working hours, workers' compensation (Karoshi), and preventive measures. *Industrial Health, 44, 537-540.*

Jackson, P., Hilditch, C., Holmes, A., Reed, N., Merat, N. and Smith, L. (2011, February). *Fatigue and Road Safety: A Critical Analysis of Recent Evidence*. London: Department for Transport

Janssen, N., Kant, IJ., Swaen, GMH., Janssen, PPM. & Schroer, KAP. (2003). Fatigue as a predictor of sickness absence: results from the Maastricht cohort study on fatigue at work. *Occupational and Environmental Medicine, 60, i71-i76.*

Keall, MD., Frith, WJ. and Patterson, TL. (2005). The contribution of alcohol to night time crash risk and other risks of night driving. *Accident Analysis and Prevention, 37, 816-824.*

Lal, SK., Craig, A., Boord, P., Kirkup, L. and Nyuyen, H. (2003). Development of an algorithm for an EEG based driver fatigue countermeasure. *Journal of Safety Research, 34(3), 321-328.*

Landstrom, U., Akerstedt, T., Bystrom, M., Nordstrom, B. and Wiborn, R. (2004). Effect on drivers' alertness of a 30 minute exposure to bright light: A field study. *Perceptual and Motor Skills, 98, 770-776.*

Leone, S., Huibers, M., Kant, I., van Schayck, C., Bleijenberg, G., and Knottnerus, J. (2006). Long-term predictors of outcome in fatigued employees on sick leave: a 4-year follow-up study. *Psychological Medicine, 36(9), 1-8.*

Lützhöft, M., Thorslund, B., K*irch*er, A. & Gillberg, M. (2007). *Fatigue at sea-A field study in Swedish shipping*. Linköping: the Swedish National Road and Transport Research Institute.

Marine Accident Investigation Branch. (2009). Report on the investigation of the grounding of Antari near Larne, Northern Ireland. Retrieved 10 May, 2012 from: http://www.maib.gov.uk/cms_resources.cfm?file=/Antari_Report.pdf

Malgorzata, Z. (1982). The role of reactivity and personalaity traits in railroad accidents. *Polish Psychological Bulletin, 13, 197-206*.

Maritime Accident Casebook. (May 20, 2010). Crete Cement Grounding: Tired Pilot, Charts Uncorrected, Compromised Water-tight Integrity. Retrieved 12 May, 2012 from: http://maritimeaccident.org/2010/05/crete-cement-grounding-tired-pilot-charts-uncorrected-compromised-water-tiht-integrity/

Marine Accident Investigation Branch. (2004). *Bridge watchkeeping safety Study*. Southampton: Department of Transportation.

Maritime Labor Convention 2006, ILO, (2006).

McCallum, M.C., Raby, M. and Rothblum, A.M. (1996). *Procedures for investigating and reporting human factors and fatigue contributions to marine casualties.* Washington, DC: U.S. Coast Guard Research & Development Center.

McCulloch, K., Fletcher, A. and Dawson, D. (2002). Fatigue management systems in aviation: an evaluation. In: IGN Susila (Eds), Kumpular Makalah: *Ergonomic*. Bali.

McKernon, S. (2008). A literature review on driver fatigue among drivers in the general public. *New Zealand Transport Agency research report 342, 66.*

Moore, E.M., Heitmann, A., Guttkuhn, R., Trutschel, U., Aquirre, A. and Croke, D. (2004, March). Circadian alertness simulator for fatigue risk assessment in transportation: application to reduce frequency and severity of truck accidents. *Aviation, space, and environmental medicine, 75(3 Suppl), A107-18.*

National Research Council. (1990). *Crew Size and Maritime Safety*. Washington, DC: National Academy Press.

National Transportation and Safety Board. (1990). *Fatigue, alcohol, other drugs and medical factors in fatal-to-the-driver heavy truck crashes*. Retrieved May 24, 2012 from:
http://www.ntsb.gov/safety/safetystudies/SS9001.htm

National Transportation and Safety Board. (1995). *Evaluation of U.S. Department of Transportation Efforts in the 1990s to Address Operator Fatigue*. Washington DC: Author.

Omdal, K.A. (2003). A survey of health and work environment onboard Norwegian ships. 7th International Symposium on Maritime Health. Tarragona: the Spanish Society of Maritime Medicine.

Parker, T.W., Hubinger, L.M., Green, S., Sargent BAMOP, L. and Boyed, R. (1997). *A survey of the health, stress and fatigue of Australian seafarers*. Canberra, A.C.T.: Australian Maritime Safety Authority.

Patraiko, D. (2006, March). Fatigue onboard-Raising awareness: The Nautical Institute reporting plan. *Seaways, 4-6*.

Pawlikowska T, Chalder T, Hirsch SR, Wallace P, Wright DJ and Wessely SC. (1994). Population based study of fatigue and psychological distress. *British Medical Journal, 308(6931),* 763-766.

Philip, P., Ghorayeb, I. & Stoohs R. (1996). Determinants of sleepiness in automobile drives. *Journal of Psychosomatic Research, 41, 279-88.*

Philip, P., Taillard, J., Guilleminault, C., Quera Salva, MA., Bioulac, B. and Ohayan, M. (1999). Long distance driving and self-induced sleep deprivation among automobile drivers. *Sleep, 22, 475-480.*

Philip, P. and Akerstedt, T. (2006). Transport and industrial safety, how are they affected by sleepiness and sleep restriction? *Sleep Medicine Reviews, 10(5), 347-56.*

Pollard, J.K., Sussman, E.D. & Stearns, M. (1990). *Shipboard Crew fatigue, Safety and Reduced Manning (Report No. DOT-MA-RD-840-90-014)*. John A. Volpe National Transportation Systems Center, Cambridge, Massachusetts.

Practical Boat Owner. (2009, June 2). *Seafarer fatigue research launched*. Retrieved June 4, 2012 from:
http://www.pbo.co.uk/news/406032/seafarer-fatigue-research-launched

Raby, M. and McCallum, M.C. (1997). Procedures for investigating and reporting fatigue contributions to marine casualties. *Paper presented at the Human Factors and Ergonomics Society 41st Annual Meeting*.

Reyner, L. & Baulk, S. (1995). *Fatigue on ferry crews: A pilot study*. Retrieved April 10, 2012 from:
http://www.sirc.cf.ac.uk/uploads/publications/Fatigue%20in%20Ferry%20Crews.pdf

Roach, GD., Dorrian, J., Fletcher, A. and Dawson, D. (2001). Comparing the effects of fatigue and alcohol consumption on locomotive engineers' performance in a rail simulator. *Journal of Human Ergology, (1-2), 125-130.*

Saaty, T.L. (2008). Decision making with the analytic hierarchy process. *International Journal of Services Sciences, 1(1), 83-98.*

Sagberg, F. (1999). Road accidents caused by drivers falling asleep. *Accident Analysis and Prevention, 31(6), 639-649.*

Seafarers International Research Centre. (1996). Seafarers International Research Centre (SIRC) for Safety and Occupational Health, In *Proceedings of a research workshop on fatigue in the maritime industry: Vol. 01.* Cardiff.

Sherry, P. (2005). A fatigue model and job performance: testing the validity of model predictions for locomotive engineers. *International Conference on Fatigue Management in Transportation Operations*. Seattle.

Smith, AP. (1999). The Problem of Fatigue Offshore. In *Proceedings of Seafarers International Research Centre First Symposium* (pp. 52-73). Cardiff University.

Smith, A., Allen, P., and Wadsworth, E. (2006). *Seafarers' Fatigue: The Cardiff Research Programme*. Retrieved May 1, 2012 from:
http://www.mcga.gov.uk/c4mca/research_report_464.pdf.2006

Smith, A.P. (2007). *Adequate crewing and Seafarers' fatigue: The International Perspective*. Retrieved June 3, 2012 from:

http://www.itfglobal.org/files/seealsodocs/3193/ITF%FATIGUE%20

Spencer, MB., Robertson, KA. and Folkard, S. (2006). *The development of a fatigue/risk index for shift workers*. Retrieved June 3, 2012 from: http://www.hse.gov.uk/research/rrpdf/rr446.pdf

Stone, B., McCuffog, A., Spencer, M., Turner, C., and Mills, A. (2005). Fatigue and shift work in UK train drivers. *International Conference on Fatigue Management in Transportation Operations*, Seattle.

Sussman, D. and Coplen, M. (2000). Fatgiue and alertness in the United States railroad industry part I: The nature of the problem. Transportation Research Part F: *Traffic Psychology and Behaviour, 3(4), 211-220*.

The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), and the STCW Code (the 2011 edition), IMO, (2011).

Tzamalouka, G., Papadakaki, M. and El Chliaoutakis, J. (2005). Freight transport and non-driving work duties as predictors of falling asleep at the wheel on urban areas of Crete. *Journal of Safety Research, 36(1), 75-84*.

U.S. Coast Guard. (1995). *Prevention through People: Quality Action Team Report*. Washington, DC: Author.

Van Amelsvoort, LGPM., Kant, IJ., Beurskens, AJHM., Schroer, CAP. & Swaen, GMW. (2002). Fatigue as a predictor of work disability. *Occupational and Environmental Medicine, 59, 712-713*.

Van Dongen, HPA. (2004). Comparison of mathematical model predictions to experimental data of fatigue and performance. *Aviation, Space and Environmental Medicine, 75, 15-36*.

Wadsworth, E. J., Allen, P. H., Wellens, B. T., McNamara, R. L., & Smith, A. P. (2006). Patterns of fatigue among seafarers during a tour of duty. *American Journal of Industrial Medicine, 49, 836-844*.

Wadsworth, EJ., Allen, PH., McNamara, RL. and Smith, AP. (2008, May), Fatigue and Health in a seafaring population. *Occupational Medicine, 58(3), 198-204*.

Wang, JS. and Knipling, RR. (1994, March). *Single vehicle roadway departure crashes: Problem size assessment and statistical description*. Washington, DC: US Department of Transport.

Warsash Maritime Academy. (2009). Horizon Research Project. Retrieved 3 May, 2012 from: http://www.warsashacademy.co.uk/research/horizon/horizon.aspx

Watanabe, Y. (2008). Preface and mini-review: Fatigue science for human health. In: Watanabe, Y., Evengard, B., Natelson, B.H., Jason, L.A. and Kuratsune, H. (Eds.), *Fatigue Science for Human Health* (pp. 5-11). New York: Springer.

Welford, AT., Brown, RA., and Gabb, JE. (1950). Two experiments on fatigue as affecting skilled performance in civilian air crew. *British Journal of Psychology, 40, 195-211.*

Wellens, B.T, McNamara, R., Allen, P.H. and Smith, A.P. (2005). Collisions and collision risk awareness at sea: data from a variety of seafarers. In P. D. Bust and P. T. McCabe (Eds.), *Contemporary Ergonomics 2005* (pp. 573-577). London: Taylor & Francis.

Wright, N., Powell, D., McGown, A., Broadbent, E. and Loft, P. (2005). Avoiding Involuntary Sleep curing civil air operations: Validation of a Wrist-worn alertness device. *Aviation, Space and Environmental Medicine, 76(9), 847-856.*

Zhou, DS. (1991). Epidemiological features and causes of railway traffic accidents. *Chinese journal of preventive medicine, 25(1), 26-9.*

Appendices

Appendix A Questionnaire concerning the selection of evaluating indexes

Dear Sir/Madam,

I am Wang Huanxin studying in World Maritime University with pursuit of my Master's degree. At present I am engaged in my dissertation as a partial fulfillment of my Degree requirements.

Therefore, I would be very much obliged, if you could assist me to obtain your opinions on the selection of the evaluating indexes for seafarers' fatigue, which are going to form the evaluation index system.

I assure that all the information provided by you will be treated as confidential and they will only be utilized for academic purposes. Please send your questionnaires **before 30 May, 2012**. Should you have any questions or comments, please do not hesitate to contact me (email: s12094@wmu.se).

Part A: General information (Please fill the space with your personal information)

1). Name:_____

2). Age:_____

3). Nationality:_____

4). Gender: ☐ Male ☐ Female

5). I work as a (your position?)_____

6). How long have you had your present position? Approximately_____years

Part B: Opinions on the selection of evaluating indexes for seafarers' fatigue

This part of the questionnaire is designed to acquire your opinion on the selection of the evaluating indexes for seafarers' fatigue. In other words, what factors should

be considered when carrying out the evaluation on seafarers' fatigue? In order to make sure the assessment flows in a logical way, the factors are divided into four categories, namely crew-specific factors, management factors, ship-specific factors and environmental factors, each of which has sub-factors, as listed in the tables.

Please tick the box in the column of "Agree" if you think the corresponding factor should be included in the evaluation index system. For example, if you think "working hours" should be chosen, just tick the corresponding box to "working hours" in the column of "Agree". If the factors you think should be included are not listed in the table, please add them to the last row.

For each factor you choose, please give a score for the extent the factor can affect seafarers' fatigue. The range of scores is 1-10, with 1 meaning the least influence and 10 meaning the greatest influence, with increasing degrees of influence in between. For example, if you think the factor of "working hours" can affect seafarers' fatigue significantly, you can mark 8 or 9 in the space in the column of "Level", corresponding to the row of "working hours".

Table (1) Selection of evaluating indexes for crew-specific factors

Crew-specific Factors	Agree	Disagree	Level
Sleep & Rest	☐	☐	
Circadian Rhythms	☐	☐	
Working hours	☐	☐	
Health	☐	☐	
Stress	☐	☐	
Ingested Chemicals	☐	☐	
Age	☐	☐	
Psychological factors	☐	☐	
Work schedules	☐	☐	

Skills & experience	☐	☐	
Any other index?			

Table (2) Selection of evaluating indexes for management factors

Management Factors	Agree	Disagree	Level
Level of manning	☐	☐	
Paperwork requirement	☐	☐	
Company culture	☐	☐	
Rules & regulations	☐	☐	
Frequency of port calls	☐	☐	
Time between ports	☐	☐	
Routing	☐	☐	
Nature of duties	☐	☐	
Any other index?			

Table (3) Selection of evaluating indexes for ship-specific factors

Ship-specific Factors	Agree	Disagree	Level
Ship design	☐	☐	
Level of automation	☐	☐	
Level of Redundancy	☐	☐	
Equipment reliability	☐	☐	
Inspection	☐	☐	
Age of ship	☐	☐	
Accommodation environment	☐	☐	
Ship motion	☐	☐	
Any other index?			

Table (4) Selection of evaluating indexes for environmental factors

Environmental Factors	Agree	Disagree	Level
Ship motion	☐	☐	
Noise	☐	☐	
Vibration	☐	☐	
Temperature	☐	☐	
Weather & sea conditions	☐	☐	
Traffic density	☐	☐	
Interpersonal relationships	☐	☐	
Any other index?			

Thank you for your time and your participation!

Appendix B The results of the first batch of questionnaires

In the first batch of questionnaire survey, 60 questionnaires were distributed and 35 recycled a month later, with 30 being used in the thesis. For the questionnaires finally utilized, these questionnaires were processed and the results are summarized as follows:

1. General information

All the participants of this survey are Chinese, with 26 Males and 4 Females. They are from different kinds of fields, such as seafarers, teachers and researchers. The detailed information can be illustrated as follows:
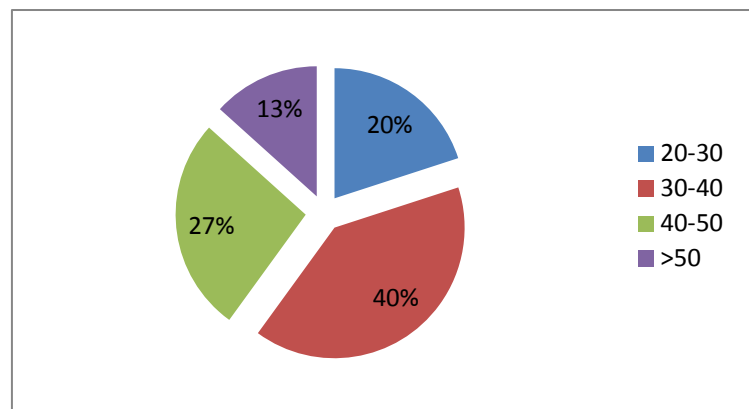
(1) Age distribution

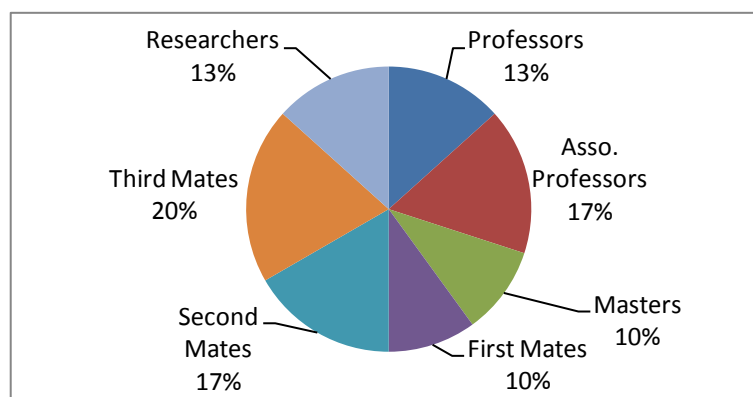Figure (1) The age distribution of the participants

(2) Job distribution

Figure (2) The job distribution of the participants

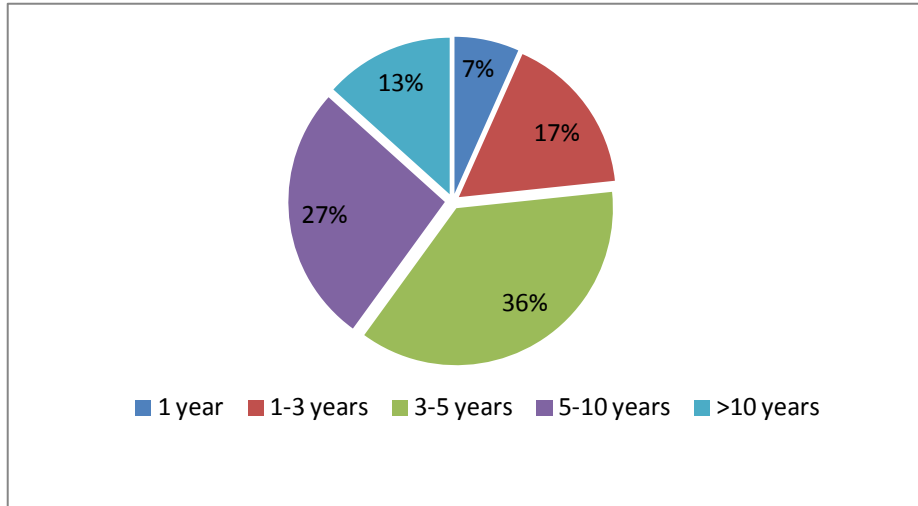(3) Distribution of length of service in present position

Figure (3) The distribution of length of the participants' service in present position

2. Opinions on the selection of evaluating indexes for seafarers' fatigue
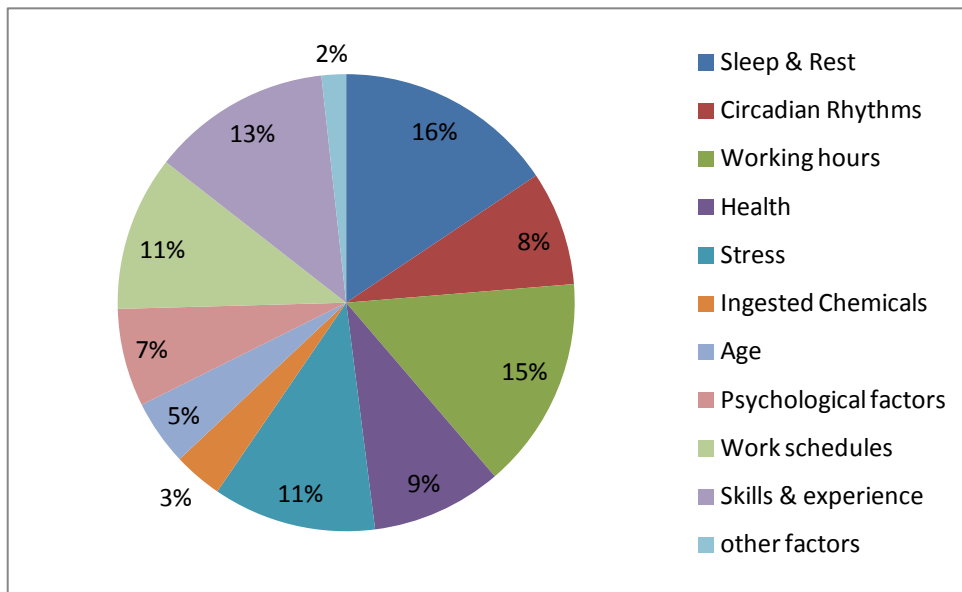
(1) crew-specific factors

Figure (4) The distribution of opinions on the crew-specific factors
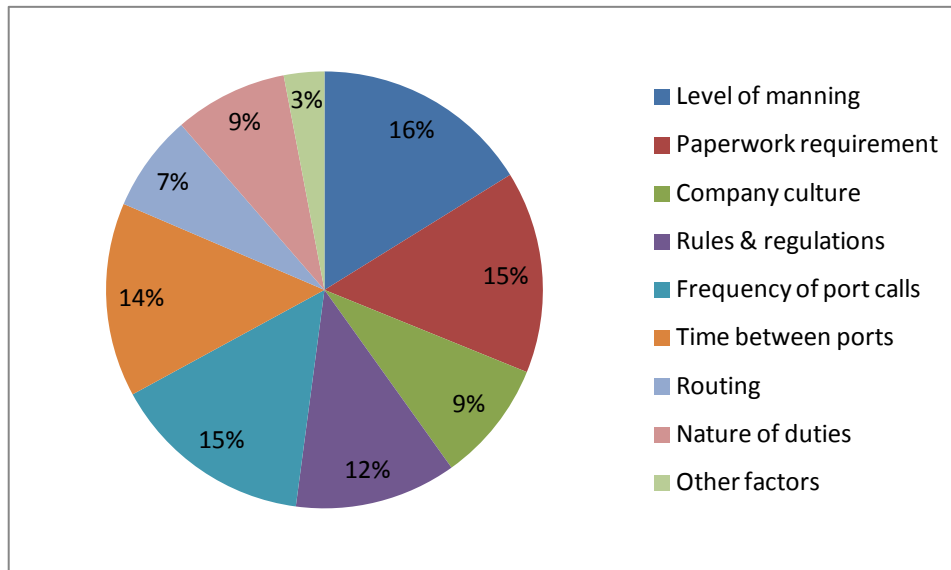
(2) management factors

Figure (5) The distribution of opinions on the management factors
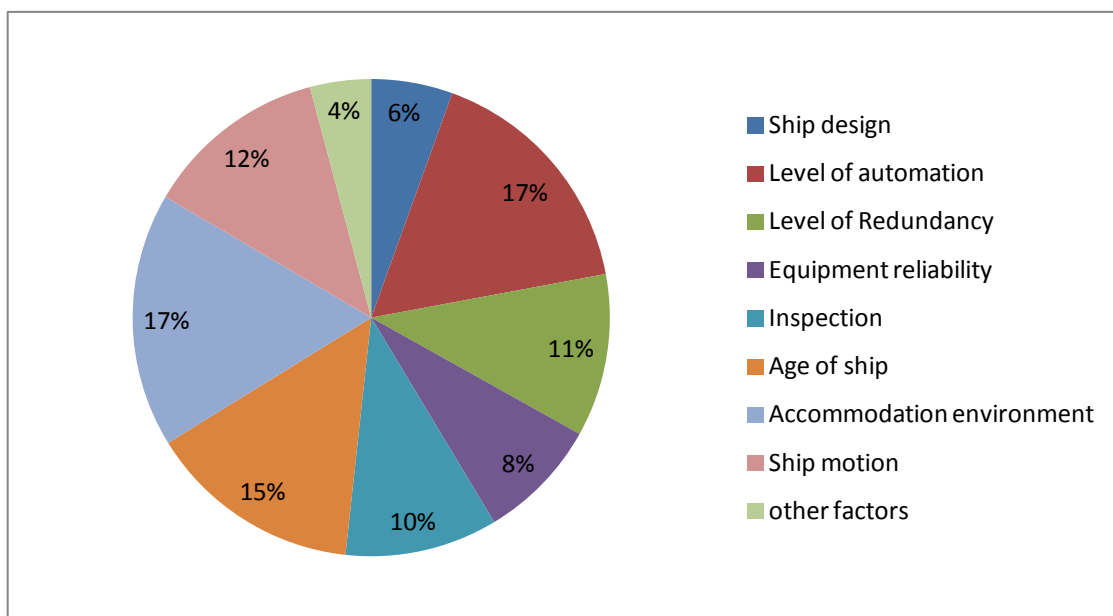
(3) ship-specific factors

Figure (6) The distribution of opinions on the ship-specific factors

(4) environmental factors
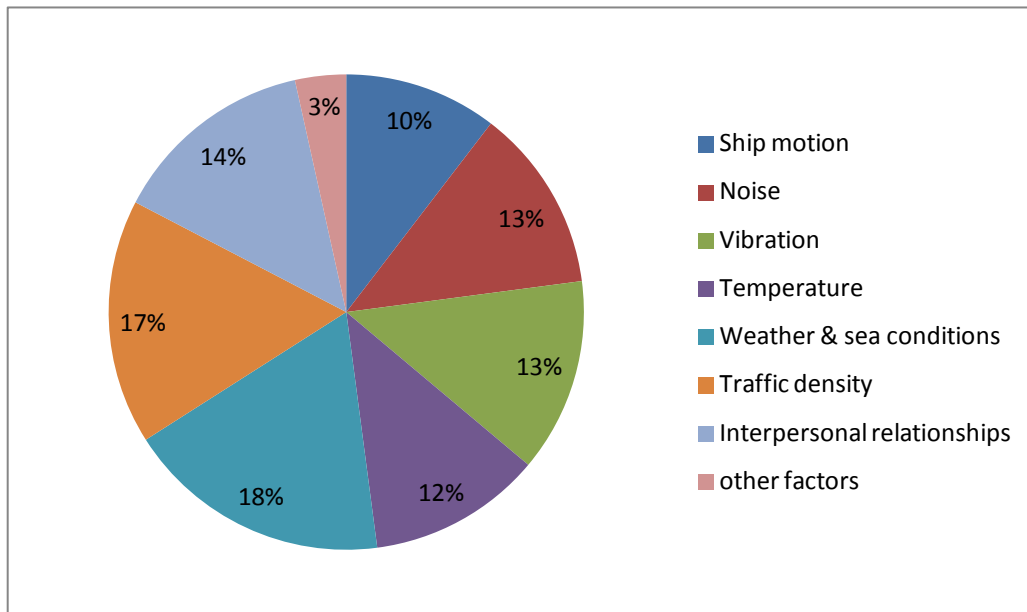
Figure (7) The distribution of opinions on the environmental factors

For each factor, three sub-factors that were chosen most are selected for the index system and will be used in the evaluation of seafarers' fatigue. In conclusion, the selected indexes are shown as follows:

(a) Crew-specific factors: sleep and rest, working hours, skills and experience

(b) Management factors: level of manning, frequency of port calls, paperwork requirements

(c) Ship-specific factors: level of automation, age of ship, accommodation environment

(d) Environmental factors: weather and sea conditions, traffic density, interpersonal relationships

Appendix C Questionnaire concerning the priority comparison of evaluating indexes

Dear Sir/Madam,

I am Wang Huanxin studying in World Maritime University with pursuit of my Master's degree. At present I am engaged in my dissertation as a partial fulfillment of my Degree requirements.

Therefore, I would be very much obliged, if you could assist me to obtain your opinions on the criteria and priority of evaluating factors.

I assure that all the information provided by you will be treated as confidential and they will only be utilized for academic purposes. Please send your questionnaires **before 30 June, 2012**. Should you have any questions or comments, please do not hesitate to contact me (email: s12094@wmu.se).

Part A: General information (Please fill the space with your personal information)

    1). Name:_____

    2). Age:_____

    3). Nationality:_____

    4). Gender: ☐ Male   ☐ Female

    5). I work as a (your position?)_____

    6). How long have you had your present position? Approximately_____years

Part B. Opinions on the evaluation criteria of indexes for seafarers' fatigue

This part of the questionnaire is designed to acquire your opinions on the evaluation criteria of the indexes for seafarers' fatigue. In my dissertation, the level of fatigue is set into five grades v_1, v_2, v_3, v_4, v_5, namely very low, low, medium, high and very high respectively. So in this step, the criterion of the factors corresponding

to each fatigue level needs to be given. In other words, for each factor, specific criterion needs to be given for each level.

For those factors that can be quantified, a certain figure or interval for each criterion should be given. Take "working hours" as an example, the criterion can be set as shown in table (1).

Table (1) The evaluation criteria for working hours (hours/day)

Rank	v_1	v_2	v_3	v_4	v_5
Working hours	<8	8~10	10~12	12~14	>14

Please fill the space for each criterion of the factors in table (2).

Table (2) The evaluation criteria of measureable indexes for seafarers' fatigue

Rank	v_1	v_2	v_3	v_4	v_5
Sleep & Rest (sleeping hours)					
Working hours (hours)					
Frequency of port calls (weeks)					
Age of ship (years)					
Traffic density (vessels/day)					

For those factors that can't be quantified, a specific score needs to be marked for each criterion. The range of scores is 1-10, with 1 meaning the greatest influence and 10 meaning the least influence, with decreasing degrees of influence in between.

Table (3) The evaluation criteria for the scores of un-measureable indexes

Rank	v_1	v_2	v_3	v_4	v_5
Score					

Part C: Opinions on the priority of evaluating indexes for seafarers' fatigue

This questionnaire is designed to obtain your opinions on the priority of the indexes. In my dissertation, the AHP is applied to determine the weight of the factors.

In the process of AHP, pair-wise comparisons at each level of the hierarchy are needed to develop relative weights to differentiate the importance of the factors.

To make comparisons, a scale of numbers is needed to indicate the relative importance of the elements. The scale used in this questionnaire is 1 through 9, with 1 meaning no difference in importance of one criterion in relation to the other and 9 meaning one criterion is extremely more important than the other, with increasing degrees of importance in between. The "reverse" comparisons simply use the reciprocal values in the matrix of comparisons that results.

Table (4) The scale of absolute numbers (1-9 Scale)

Intensity of Importance	Definition	explanation
1	Equal Importance	Two factors contribute equally to the objective
3	Moderate Importance	Experience and judgment slightly favor one attribute over another
5	Strong Importance	Experience and judgment strongly favor one attribute over another
7	Very Strong Importance	An attribute is strongly favored and its dominance demonstrated in practice
9	Extreme Importance	The evidence favoring one attribute over another is of the highest possible order of affirmation
2,4,6,8	Between the adjacent importance	When compromise is needed
Reciprocals of the above	The "reverse" comparisons of the above comparisons (eg. the result of j to i is the reciprocal of i to j)	

For example, in Row A, factor A is moderate important to factor B，then insert "3" in the intersection of Row A and Row B；Factor C is moderate important to factor A, then insert "1/3" in the intersection of Row A and Row C. In Row B, the importance of factor C to factor B is between "Moderate Importance" and "Strong Importance", then insert "4" in the intersection of Row B and Row C. The example can be shown in table (5).

Table (5) Example of the priority comparision

	A	B	C
A	1	3	1/3
B		1	4
C			1

Table (6) The priority comparison of first-level indexes

	Crew-specific factors	Management factors	Ship-specific factors	Environmental factors
Crew-specific factors	1			
Management factors		1		
Ship-specific factors			1	
Environmental factors				1

Table (7) The priority comparison of crew-specific indexes

	Sleep & Rest	Working hours	Skills & experience
Sleep & Rest	1		
Working hours		1	
Skills & experience			1

Table (8) The priority comparison of management indexes

	Level of manning	Frequency of port calls	Paperwork requirement
Level of manning	1		
Frequency of port calls		1	
Paperwork requirement			1

Table (9) The priority comparison of ship-specific indexes

	Level of automation	Age of ship	Accommodation environment

Level of automation	1		
Age of ship		1	
Accommodation environment			1

Table (10) The priority comparison of environmental indexes

	Weather & sea conditions	Traffic density	Interpersonal relationships
Weather & sea conditions	1		
Traffic density		1	
Interpersonal relationships			1

Thank you for your time and your participation!

Appendix D The results of the second batch of questionnaires

In the second batch of questionnaire survey, 52 questionnaires were distributed and 32recycled, with 30 being used in the thesis. For the questionnaires finally utilized, these questionnaires were processed and the results are summarized as follows:

1. General information

All the participants of this survey are Chinese, with 28 Males and 2 Females. Since the second batch of questionnaire survey was carried out based on the results of the first batch of survey, the questionnaire were first distributed to the same investigators in the former investigation as well as to a number of other experts. The detailed information of these participants can be illustrated as follows:
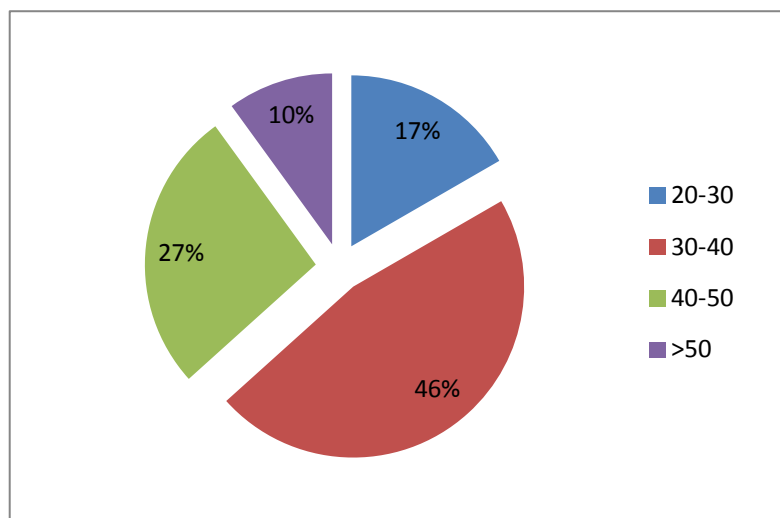
(1) Age distribution

Figure (1) The age distribution of the participants
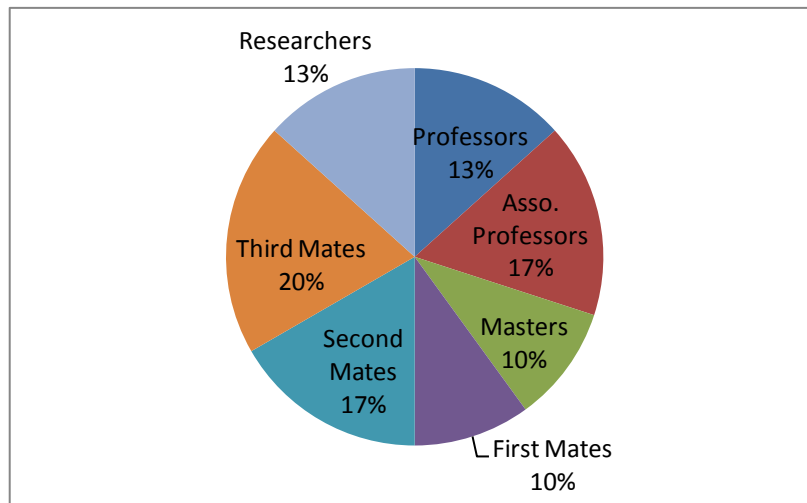
(2) Job distribution

Figure (2) The job distribution of the participants

(3) Distribution of length of service in present position
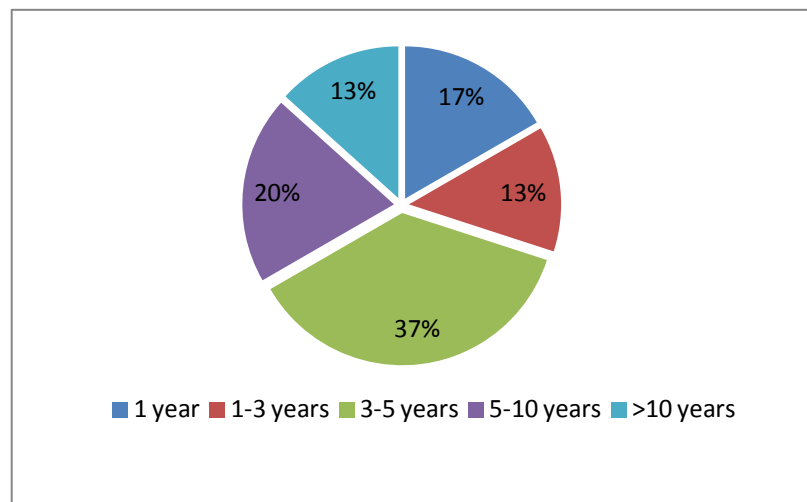

Figure (3) The distribution of length of the participants' service in present position

2. Opinions on the criteria of evaluating indexes for seafarers' fatigue

The data for the criteria of these indexes was collected and then the method of weighted average is used to deal with these data. As a result, the final criteria of these indexes are shown in the following tables.

Table (1) The criteria for measurable indexes

Rank	v_1	v_2	v_3	v_4	v_5
Sleep hours	>7	5.5~7	4.5~5.5	3~4.5	<3
Working hours	<8	8~10	10~12	12~14	>14
Time between port calls	>3	2~3	1~2	3/7~1	<3/7
Age of ship	<3	3~5	5~10	10~18	>18
Traffic density	<200	200~400	400~600	600~800	>800

Table (2) The criteria for non-measurable indexes

Rank	v_1	v_2	v_3	v_4	v_5
Score	>9	7~9	5~7	3~5	<3

3. Opinions on the priority of evaluating indexes for seafarers' fatigue

The comparative priority of these factors was collected and then the method of weighted average was used to deal with these data. As a result, the final results of priority comparison of these factors are shown in the following tables.

Table (3) The priority comparison of first-level indexes

	Crew-specific factors	Management factors	Ship-specific factors	Environmental factors
Crew-specific factors	1	2	2	3
Management factors		1	1	2
Ship-specific factors			1	2
Environmental factors				1

Table (4) The priority comparison of crew-specific indexes

	Sleep & Rest	Working hours	Skills & experience
Sleep & Rest	1	2	4
Working hours		1	3
Skills & experience			1

Table (5) The priority comparison of management indexes

	Level of manning	Frequency of port calls	Paperwork requirement
Level of manning	1	2	3
Frequency of port calls		1	2
Paperwork requirement			1

Table (6) The priority comparison of ship-specific indexes

	Level of automation	Age of ship	Accommodation environment
Level of automation	1	2	1
Age of ship		1	1/2
Accommodation environment			1

Table (7) The priority comparison of environmental indexes

	Weather & sea conditions	Traffic density	Interpersonal relationships
Weather & sea conditions	1	2	3
Traffic density		1	2
Interpersonal relationships			1