

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**A HUMAN FACTOR ANALYSIS APPROACH TO PREVENT FIRE SAFETY
RELATED DEFICIENCIES ON BOARD SHIPS**

M.Sc. THESIS

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Department of Maritime Transportation Engineering

Maritime Transportation Engineering Programme

MAY 2015

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**GEMİLERDE YANGIN EMNİYETİ İLE İLGİLİ UYGUNSUZLUKLARIN
ÖNLENMESİNE YÖNELİK BİR İNSAN FAKTÖRÜ ANALİZİ YAKLAŞIMI**

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To my family,

FOREWORD

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ABBREVIATIONS

ABS	: American Bureau of Shipping
DNV	: Det Norske Veritas
EMSA	: European Maritime Safety Agency
FCM	: Fuzzy Cognitive Map
FSA	: Formal Safety Assessment
HFACS	: Human Factor Analysis and Classification System
IACS	: International Association of Classification Societies
IMO	: International Maritime Organizations
ISO	: International Organisation for Standardisation
MOUs	: Memorandum of Understandings

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A HUMAN FACTOR ANALYSIS APPROACH TO PREVENT FIRE SAFETY RELATED DEFICIENCIES ON BOARD SHIPS

SUMMARY

Transportation has a magnificent prominence that is because modern human life strongly needs safe, secure, environmental, and sustainable transportation systems. Maritime transportation has a privileged position among the other transportation systems regarding its contribution to the global world trade. According to the UNCTAD' review of the recent maritime transportation report, over the 80 % of the world cargoes carried by shipping industry. On the other hand, maritime accidents have a tremendous potential for leading to catastrophic damage to crews, passengers, cargo, ship, and marine environment. Especially, fire/explosion accidents are one of the most encountered maritime accidents. At this point, International Maritime Organization (IMO) implemented some amendments on the ISM Code to improve maritime safety via the shift the corrective action paradigm to proactive approach in 2010. In this way, maritime shareholders might prevent accidents before they happened. However, this new paradigm also brings some challenges for the maritime shareholders such as; development of the advanced methods and the lack of research gaps in maritime literature based on the proactive approach.

From this viewpoint, the research combines the HFACS and FCM methodologies in order to overcome the mentioned challenges. Firstly, PSC investigation reports and related competent authorities' reports are investigated in detail for the identified the cause of the fire related deficiencies. Next, these causes are classified according to the HFACS framework. After this point, FCM is utilized to prioritization the causes. Moreover, hidden root causes might have a great influence on systems, therefore; indirect relation between the deficiencies are also analysed. According to the revealed root causes, Safe Ship System Mechanism (SSSM), Safe Ship Operation Mechanism (SSOM), Safe Ship Execution Mechanism (SSEM) is suggested in order to increase the effectiveness of the measures.

Consequently, the study contributes to both maritime industry and maritime safety literature. Developed the proactive model that reveals the root causes; therefore improve the fire-fighting capability is the industrial contribution. The maritime safety literature contribution is that using advanced scientific methodologies, so close research gaps in the literature.

GEMİLERDE YANGIN EMNİYETİ İLE İLGİLİ UYGUNSUZLUKLARIN ÖNLENMESİNE YÖNELİK BİR İNSAN FAKTÖRÜ ANALİZİ YAKLAŞIMI

ÖZET

Deniz yolu taşımacılığının, dünya ticaretindeki önemi gün geçtikçe artmaktadır. Bu önem yalnızca taşınan yük miktarı ile ilgili olmayıp aynı zamanda gerçekleştirilen taşımanın ekonomikliğı dolayısı ile şirketlere kazandırmış olduğı rekabet avantajı ile de yakından ilgilidir. Bunların ötesinde, deniz yolu taşımacılığının verimli ve güvenli olması sebebiyle de dünya ticaretine olumlu yönde katkıları söz konusudur. Bu katkıların öncelikle etki düzeylerinin artırılması ve daha sonra bu katkılara yenilerinin eklenmesi için denizcilik endüstrisine büyük sorumluluklar ve ödevler düşmektedir. Bu ödevlerden başlıcası; denizcilik sektöründeki emniyet düzeyinin artırılması hususudur. Deniz kazalarını bu bağlamda incelediğimizde, deniz emniyetini riske atan ve gerek gemi, yolcu, mürettebat ve yüke ve gerekse de çevreye büyük tahribalar veren belli başlı birkaç kaza türü gözlemlenmektedir. Bunlardan en önemlilerinden birisi ise; Yangın/Patlama kaynaklı kazalardır. Bazı klass kuruluşlarının ve liman devletlerinin yapmış oldukları denetim sonuçları incelendiğinde, yangın/patlama ilgili eksiklerin tespit edilen toplam eksiklere oranı yaklaşık %15-25 olarak belirtilmektedir. İlgili kaynakların ortaya koyduğı daha çarpıcı diğeri bir sonuç ise, söz konusu eksikliklerin tekrarlayan bir şekilde ortaya çıktığı ve deniz emniyetini riske attığıdır.

Deniz yolu taşımacılığının yasal düzenlemelerini meydana getirerek bu düzenlemelerin tartışılmasına ve geliştirilmesine ev sahipliğı yapan Uluslararası Denizcilik Örgütü (IMO) 2010 yılında ISM Code’da yapmış olduğı değişiklikler ile tekrarlanan bir şekilde ortaya çıkan eksikliklerin giderilmesi ile ilgili olarak denizcilik firmalarına yeni bir takım sorumluluklar yüklemiştir. Örneğin; şirketlerden yönetmelik ve/veya kodlara ilgili olan uyumsuzlukların kayıt altına alınıp raporlanması ve bunların ilgili kök sebeplerinin ortaya çıkarılması için gerekli önlemlerin alınması beklenmektedir. Bu yeni yaklaşım ile önceki yıllara ait olan düzeltici önlem yaklaşımı proaktif yaklaşım şeklinde düzenlenerek bir paradigma değişimi gerçekleştirilmiştir. Böylelikle tekrarlayan bir şekilde ortaya çıkan eksikliklerin giderilmesi konusunda şirketler sorumlu tutularak teşvik edilmektedirler. Her ne kadar bu yeni düzenlemeler ile önerilen proaktif yaklaşım çok önemli ve hayati olsada, denizcilik firmalarının bu konudaki alt yapı eksiklikleri ve bu yeni yaklaşımı hayata geçirmeleri noktasında ihtiyaç duyacakları yeni bilimsel çalışmaların yeterli düzeyde olmaması, bu yeni yaklaşımla beraber denizcilik firmalarının karşılaştığı temel sorunlardan bazılarıdır. Bu sebeple denizcilik endüstrisinde proaktif yaklaşımı temel alan çalışmalara büyük bir ihtiyaç duymakta ve bu konuda önemli bilimsel çalışmaların eksikliği hissedilmektedir.

Söz konusu olan paradigma değişikliğı ve sonucunda ortaya çıkan ihtiyaçlar ve bilimsel çalışma eksiklikleri doğrultusunda, bu çalışma; HFACS-FCM modellerini

etkili bir şekilde kullanarak, yangın ile ilgili eksikliklerin kök sebeplerini ortaya çıkararak daha etkili yangın önlemleri alınmasını sağlamak ve en nihayetinde gemilerin yangın emniyetlerinin artırılmasını amaçlamaktadır.

Bu noktadan hareket ile denizcilik şirketleri ve yetkili otoriteler tarafından yayınlanmış olan yangın ile ilgili eksikliklerinin yer aldığı raporların incelenmesi çalışmanın başlangınç aşamasını oluşturmaktadır. Bu aşamada ilgili raporlardan oluşan bir database oluşturulmuş ve incelemeler ayrıntılı bir şekilde yürütülmüştür. Ayrıntılı olarak incelenen raporlar doğrultusunda yangın ile ilgili eksiklikler 20 ayrı kategoriye ayrılmıştır. Sonrasında her kategori için eksikliklere neden olabilecek sebepler tespit edilmiştir. Tespit edilen sebepler HFACS modeli tarafından önerilen 4 ayrı sınıflandırmaya tabi tutulmuştur. Yapılmış olan sınıflandırma neticesinde, sebeplerin ortaya çıkmasında etkili olan sınıfın tesbiti mümkün olduğundan daha etkili bir önlem alınmasına imkân sağlanmış olmaktadır.

Ancak çalışmanın temel amacı eksikliklere neden olan kök sebepleri ortaya çıkarmak olduğu için çalışmanın burdan sonraki aşamaları bu kök sebepleri ortaya çıkarmaya yönelik olacaktır. Bu noktada kök sebeplerin ortaya çıkarılması için FCM'den faydalanılmıştır. FCM gerek yeterli data'nın bulunmadığı ve uzman görüşlerinin kullanılmasına imkân sağladığı ve gereksede işlemlerinin basit ve model oluşturmada sağladığı kolaylıklar sebebi ile bu çalışmada tercih edilmiştir.

Yangın ile ilgili sebeplerin sınıflara ayrılmasından sonra, söz konusu sebepler arasındaki ilişkilerin belirlene bilmesi için uzmanlar dilsel değerlendirme skalası yardımıyla sebepler arasındaki ilişkilerin derecelendirilmesini yapmışlardır. Bu ilişkilerin ilgili uzmanlar tarafından belirlenmesi ve tüm ilişkilerin tek bir uzman tarafından belirlenemeyeceği gerçeğinden hareketle, ilişkileri belirten bir tablo oluşturulmuş ve bu tablo 7 ayrı uzmanlık alanına ayrılmıştır. Yapılan değerlendirmeler neticesinde elde edilen veriler incelenerek, potansiyel kök sebeplerin tespiti gerçekleştirilmiştir. Ancak belirtildiği gibi bu işlem yalnızca potansiyel kök sebepleri ortaya çıkarttığı için saklı kök sebeplerin incelenmesine de ihtiyaç duyulmaktadır, çünkü saklı kök sebepler bazen sistem üzerinde büyük etkilere sebep olabilmektedirler. Saklı kök sebeplerin tespiti için ise direkt olmayan ilişkiler incelenmiştir. Direkt ve direkt olmayan ilişkiler incelendikten sonra, kalitatif simülasyon kullanılarak bir sebebin sistem üzerinde etkisi ve bu sebep aktif olduğu taktirde hangi aşamada sistemin sabit bir düzeye ulaştığı incelenmiştir. Bu sonuçlar neticesinde saklı olan kök sebeplerin tespiti gerçekleştirilmiştir.

Çalışmanın son aşamasında, tespit edilmiş kök sebeplere karşı önleyici tedbirlerin alınması için bazı kapsayıcı önerilerde bulunulmuştur. Bu önerilerin etkinliği artırmak amacıyla kök sebepler kendi aralarında sınıflandırılarak önerilen tedbirlerin etkinliğinin ve faydasının artırılması amaçlanmıştır.

Sonuç olarak, yürütülmüş olan çalışma ile denizcilik sektörünün emniyet seviyesini artırmak amacıyla IMO tarafından yürürlüğe konan regülasyonlar çerçevesinde ortaya çıkan bilimsel çalışma eksikliği giderilmeye çalışılmıştır. Dahası, denizcilik endüstrisinin ihtiyaç duyduğu ve etkinliği diğer çalışmalarda doğrulanmış olan gelişmiş bilimsel yöntemler kullanarak, proaktif yaklaşımı temel alan bir çalışma yangın emniyetini artırmak noktasında gerçekleştirilmiştir. Yangının önlenmesinde karşılaşılan zorluklar ve denizcilik endüstrisinin çalışma ortamının bu zorluklara olan

pozitif katkısı göz önüne alındığında, bu çalışmanın denizcilik endüstrisine büyük katkılar sağlayacağı aşikârdır. Kullanılmış olan yöntemlerin etkinliği ve elde edilen verilerin kapsayıcılığı dolayısı ile de çalışmanın bilimsel katkısı da büyük önem arz etmektedir.

Mevcut çalışmanın ileri bir aşaması olarak, uzman sistemlerin geliştirilebileceği ve bu noktada yapılacak çalışmalara denizcilik ve diğer yüksek risk içeren endüstrilerde, gelişmiş bilimsel modeller kullanan çalışmalara ihtiyaç duyulduğu gözlemlenmektedir.

1. INTRODUCTION

In this century, total trade volume of the world is at the largest level as it has never been before. Financially, it is called as globalization. Naturally, this phenomenon affects many aspects of the world and the way people do business, as a whole (Kumar and Hoffmann, 2002). In addition, increasing economic, financial and social expectations in parallel with technological enhancements pushes the international organizations, governments and local administrations to improve the education and health systems, and transportation services to achieve better life standard. Among those fundamental systems and services, transportation has a magnificent prominence that is because modern human life strongly needs safe, secure, environmental, and sustainable transportation systems (Corbett and Winebrake, 2008).

Maritime transportation has a privileged position among the other transportation systems regarding its contribution to the global world trade. According to the UNCTAD' review of the recent maritime transportation report, over the 80 % of the world cargoes carried by shipping industry (UNCTAD, 2013). In parallel with that, maritime transportation enables ship-owners to operate mass transportation, in this way; freight for per unit cost decreases tremendously. Maritime transportation is one of the most cost-effective methods, especially, in terms of long-distance transportation (Hu and Zhu, 2009), so that; it is an indispensable component of the world economy (Christiansen et al. 2006).

Due to its nature, maritime transportation is a global industry, therefore; it has international relations with many other industries (Guerrero and Rodrigue, 2014). Besides, it has a great importance on the transportation of the production goods and the energy transportation such as oil and natural gas, etc. The world food security also inevitably depends on the maritime transportation as well. Huge cities desperately need the imported food products to meet their demand. Thereby, maritime transportation affects all countries in the world, whether they are coastal or not (IMO, 2013).

The United Nations (UN) Conference on the Human Environment was held in Stockholm in 1972. It caused a dramatic change of the economic development paradigm. For the first time, negative impacts of the economic growth were considered, as a global issue. Afterwards, international organizations, governments, and local administrations have used their legislative authorities in order to reduce or prevent the environmental pollution as much as possible. Public awareness and the expectations are also increased to preserve the world's natural resources, in reaction to the excessive environmental pollution. Therefore, environmentally friendly transportation systems have come into prominence. At that point, maritime transportation systems provided a great opportunity to reduce the harmful impacts of the current transportation systems or modes over the environment. Thanks to International Maritime Organization's (IMO), conventions, codes, and amendments, maritime transportation continuously improves its procedures to maintain one of the world's cleanest transport services (IMO, 2013).

Moreover, maritime transportation is a regulated industry, particularly by IMO, which is a UN specialized agency, and responsible for the maritime transportation legislative and technical framework. Hence, it has a relatively safe and secure historical background. IMO regulates all technical, operational, managerial aspects of the maritime transportation in terms of safety and security perspectives. IMO has developed and implemented hundreds of codes and guidelines, which cover the operational lifetime of commercial ships. Most importantly, IMO constantly makes an effort to improve those regulations concerning marine stakeholders' needs and technological advancements (IMO, 2013).

On the other hand, maritime accidents can cause catastrophic damages over the crews, passengers, cargo, ship, and marine environment (Skjong and Soares, 2008). More importantly, maritime accidents compromise the effectiveness of this substantial transportation system's safety, therefore; maritime accidents are needed to be kept under control, and supervised before they happen. With this insight, the study has investigated the fire related deficiencies in order to improve the fire safety in maritime domain.

1.1 Motivation on Fire Safety on board Ships

Fire accidents are one of the most encountered maritime accidents. According to the surveys, among the all type of accidents in merchant shipping over a period of 25 years, fire based accidents have caused a massive loss after grounding. Fire on commercial ships is leading quite often to total loss of the ship and/or her cargo, and to loss of human life. History of the maritime transportation exemplifies how fire accidents in maritime domain can be devastating therefore; several noteworthy fire accidents are investigated.

The Titanic disaster was the most popular and devastating maritime accident that caused the death of more than 1500 people in the history. Titanic sank in the North Atlantic Ocean in 1912 after colliding with an iceberg. The Titanic carried 2,224 passengers and crew, although; she only carried enough lifeboats for 1,178 people. Therefore, the accident caused a huge loss of life. After the Titanic disaster, important enhancements discussed among the international committees about the maritime safety (Çevik, 2012). Consequently, International Convention for the Safety of Life at Sea (SOLAS) was established in 1914, which still governs the maritime safety today. However, the 1914 SOLAS Convention did not enter into force because of the World War I (Frey et al. 2011).

In 1934, SS Morro Castle, which was a luxury ocean liner, caught fire and burned while she was operating between New York and Havana by killing its 137 passengers and crew members. The accident investigation report demonstrates several critical causes for such a high number of deaths. Firstly, the initial strategy was to attempt to berth the ship to the shore instead of using SOS transmission. As a result, before the fire burned the ship's main electrical cables, the crews were not managing to make a single SOS transmission. Secondly, the ship was made of highly flammable materials; therefore, the fire spreaded quickly and it was hard to control the fire for the crews (Çevik, 2012).

The Texas City disaster was one of the most deadly ship oriented industrial accident, which at least 581 people killed, and more than 3000 people were seriously injured. Quickly spreaded fire and ammonium nitrate explosions affected two ships, and damaged highly at Texas City, Texas, April 16, 1947. Beside that, property damage and contingent costs were estimated at \$67,000 000. It was believed that one or more

crew smoked cigarettes during the rest interval on board of the SS Grandcamp, which was docked in the port. That was the origin of the initial fire, and it caused a mass explosion of approximately 2,300 tons of ammonium nitrate. The sparks spreaded to The SS High Flyer, which was docked about 200 m away from the SS Grandcamp. Unfortunately, it was loaded with 961 tons of ammonium nitrate and 1,800 short tons of sulphur. In the beginning, as the second captain ordered, crews had responded the fire without using water because it would damage the cargo. Within 15 minutes, despite the effort to smooth the fire, the smoke could not be controlled. After that point, the Texas City Fire Department received an emergency call for fire. Consequently, the highly explosive chemical products and late response intensified the damage, and the attempts were ineffective. As a result, preparedness, prompt detection and reporting the fire on time are the key to control the fire effectively. Furthermore, to make quick response to any fire involved disaster, fire prevention units were required to settle near to certain industrial facilities.

On 22 December 1963, The TSMS Lakonia, which was a cruise-liner ship, caught fire and sank north of Madeira with the loss of 128 lives. Most of the casualties died not only due to the fire but also due to exposure and drown, also some died while they were trying to escape from the fire by jumping from the deck. Firstly, a steward noticed that a black smoke was leaking out from the ship's hairdressing salon. After that, the steward and co-worker tried to put out the fire with extinguisher; however, the fire spreaded so quickly. Moreover, most passengers did not hear fire alarm because it was not loud enough and some passengers were at sleep during the disaster (Çevik, 2012). Even the lifeboat drill had been conducted a week ago before the accident occurred, evacuation process was not conducted smoothly because chains of the davits had rusted, so; moving to the lifeboats became very difficult and some lifeboats were burned before they could be lowered. Ultimately, the reason of the fire was determined to be a short circuit of faulty electrical wiring.

Moreover, the human element is another critical component of the maritime transportation, which has an important role in the maritime safety. According to maritime accident statistics and investigation reports, the human element is one of the primarily contributing factors to maritime accidents (Darbra and Casal. 2004; Toffoli et al. 2005). Thus, it has a great potential contribution to improvements on

the maritime safety. Therefore, maritime researchers pay significant attention to the role of the human element in maritime accidents.

As conclusion, all the facts that mentioned above point out that; to keep maritime transportation systems safe, secure, and effective; maritime stakeholders must consider taking advantage of the scientific methods. Especially, fire related accidents or deficiencies have great potential to jeopardize maritime safety and yet again, the human element is a predominant factor, which causes such maritime accidents. Therefore, the study is conducted in the purpose of preventing fire safety related deficiencies on board ships.

1.2 Thesis Objectives

Fire related deficiencies and accidents are ones of the most encountered phenomenon that endanger crews, cargoes, ships, and environmental safety. For instance, considering that a fire related accident happens on a cruise ship which has the capacity to carry thousands of people or ships that carry hazardous cargoes, one can easily conceive its possible and unfortunate consequences. From this perspective, the main objective of this thesis is to discuss and suggest a proactive fire safety model to inhibit possible accidents before they happen or to prevent reoccurrence of the fire safety related deficiencies and accidents on merchant ships. For this reason, the study is magnificently important regarding maritime safety regulations' implementations after the catastrophic accidents.

Despite the high-tech navigational aid equipments, automatic operational devices, and implementation of hundreds of codes and guidelines, marine accidents are still not at the desired level that it is expected, because maritime transportation is a system, which heavily based on the human element. Hence, this study considers that the human element is one of the substantial components that threatens the maritime safety. Consequently, the study also aims to detail the investigation of the human element role on fire safety subject.

Moreover, the study aims to enhance the fire prevention capability of the shipowners, companies, or entrepreneurs as well. That will also reduce the risk factor for the stakeholders. Once we aware of the deficiencies that might jeopardize ship safety, it is easy to take any necessary measures against them. Therefore, the study reveals the

root cause/s of the deficiencies in order to enhance the fire prevention capability of companies and stakeholders. To ensure fire safety, the first step is to take preventive measures. As a result, this study provides praiseworthy contributions for fire safety on merchant ships.

Further, the study aims to develop flexible preventive action models, which can be practical not only for a single ship but also for larger fleets or even for related industrial processes. Thereby, it can be applicable for a wide range of relevant areas.

The present study also intends to provide a scientific and systematic model to prioritize fire related deficiencies and eliminate possible causes. In order to do that, the study is incorporated with expert opinions and sample database information under the beneficial scientific models. Therefore, the study has been also conducted with the FCM simulations, which increases model's integrity. To do this, the study takes advantage of enormously wide sample database and gathered expert opinions to generate inclusive framework.

Beyond of all these objectives, this study also aims to make a significant contribution to the maritime safety literature. It is one of the first studies that provides a fresh and proactive approach, which enables executives and designers to take necessary precautions before the deficiencies or even accidents occur.

As a matter of fact that the human element is the most crucial factor, which causes maritime accidents, hence; the study analyses the human element role about fire related deficiencies with respect to the HFACS model in order to clarify the human role in this complex system.

1.3 Thesis Organization

This sub-section consists of detailed description of the present study's chapters. Firstly, the present study begins with introduction part as a motivation of maritime transportation and its importance to the world's global trade. Generally, the introduction part justifies the reasons that influenced this study. Particularly, in the introduction part, the value of the maritime transportation is analysed in a large scope. In connection with that, certain maritime transportation accidents are discussed in the light of the investigation reports. The purpose of the mentioning accidents is to emphasise the importance of the fire safety on board ships. The

significance of the human factor in maritime safety is highlighted in the introduction part, as well.

Second part of the study is an overview of the maritime safety literature. That sub-section covers the examination of numerous published scientific studies, which mainly investigate safety on board ships or the human factor in maritime transportation. To be more specific, the present study classifies the examined study into four important aspects of maritime safety: i) regulatory framework, ii) human factor, iii) technological improvements, iv) methodological approaches. Targeted contributions to the maritime literature and industry explicitly states in that sub-section.

The following sub-section of the second part contains methodological backgrounds and their applications. Essentially, that sub-section introduces scientific and systematic models, which are used to construct the fundamentals of the present study. The utilized models in this study are HFACS and FCM. Along with that sub-section, HFACS and FCM models are presented and mentioned in their specific characteristics. The models' applications and related literature also examined in detail, so as to capture the latest developments in these areas. More importantly, model development is plainly described in that sub-section. The model conceptualization and its application stages also help to demonstrate the model framework.

Technical background is the fourth sub-section of the study. That sub-section aims to examine all the aspects of the technical background. The technical aspects of the study are discussed as follow; i) an overview of the fire related accidents at sea, ii) fire prevention systems on-board ships, iii) regulations and procedural aspects, iv) fire frightening, v) training, vi) enhancements of the marine technology.

Another sub-section that generates the present study is the case study part. The case study part fundamentally demonstrates the implementation of the model in a scientific manner. That sub-section starts with a description of a problem. The description and scope of application clarifies the basic parameters of the problem which define the problem boundaries. HFACS model is used for the reason of categorizing the impacts of the human factors, whereas FCM model used for the

prioritize the causes of fire related deficiencies. In the last part, the integration chart demonstrates a preventive action planning.

Final sub-section of this study gives recommendations and the conclusion of the thesis. In this sub-section, study results are considered elaborately in order to obtain a comprehensive and detailed solution. From this perspective, the study provides advanced detailed graphics and charts in order to grape the detailed solutions.

2. MARITIME SAFETY LITERATURE OVERVIEW

2.1 Classification of Studies

Maritime safety has been one of the most concerned topics in maritime literature. The human element, technological advancement, legislative framework, methodological approaches are the fundamental components of the maritime transportation. Therefore, to fulfill an acceptable safety level in maritime transportation, all of these components must be delivered in a sufficient, coherent, and efficient way with one another. To achieve sustainable, cost effective, and environment friendly transportation system, maritime shareholders should dedicate themselves to improve maritime safety. Despite the notable efforts of the maritime shareholders, maritime transportation safety level has not reached the desired level. Moreover, the statistics of the maritime accidents clearly show that the numbers of the cases are far more than an acceptable level. Therefore, any contribution to increase the safety level and awareness at sea is highly important. To review the course of existing studies on maritime safety, the study represents a wide range of literature survey. The rest of the survey is conducted along with the four important aspects of maritime safety; i) regulatory framework, ii) human factor, iii) technological improvements, iv) methodological approaches.

Regulatory framework is the first aspect of the maritime literature that will be investigated in this study. IMO is the prime international organization that develops and implements the maritime regulations. However, IMO has no authority to enforce these regulations. For this basis, there is a continuous debate about the effectiveness of these regulations among the maritime transportation shareholders. Thus, numerous investigations are implemented to evaluate the IMO' regulations by the maritime researchers and practitioners. Some of these studies are mentioned in the further pages.

Tzannatos & Kokotos (2009) investigated the Greek flagged ship accidents, which cover the period from 1993 to 2006, to measure the human reliability on maritime

safety. The investigation was important because it compared the pre-and post-ISM period therefore; the result enabled researchers to assess the effectiveness of the implementation of the ISM Code. The utilized dataset gathered from Hellenic Coast Guard official investigation reports that contain all the accidents of Greek flagged ships worldwide. The accidents were analysed through a decision tree analyse method, which states the factors and the classifications of various accidents. Investigators classified the accidents, and some eliminated for the sake of the study. To illustrate; the accidents involved with identical accident information, missing values, unreliable data and the vessels under 500 grt were discarded. According to the results, ISM Code was proved to be an effective policy, which measures and regulate the shipping safety. ISM Code accomplished a remarkable reduction of human-induced accidents, although it did not discharge the influence of navigational location on the source of shipping accidents.

Knapp & Franses, (2009) developed a model to evaluate the effects of the major international conventions regarding to safety, pollution, search and rescue, and work related areas. The study utilized standard econometric models and 50,367 different cases from IMO, Lloyd's Register Fairplay (LRF) and Lloyd's Maritime Intelligence Unit (LMIU) that occurred between the years of 1977 and 2007 were gathered and used. By doing this analysis, the researchers had a chance to measure the effectiveness of the international conventions and relevant amendmends by using advanced econometric models. The analysis studied 45 different important legislative frameworks, which are realted to ship economic cycles, safety inspections and other unilateral legislation. Morover, the study divided data as a pre-and-post period of regulation in an attempt to get satisfactory results. The study ended with detailed results about each convention.

Celik (2009) proposed a model to enhance(increase) the convenience level of the International Safety Management (ISM) Code with ISO 9001:2000 so as to generate an integrated quality and safety management system (IQSMS) for shipping operations. Multi- attribute fuzzy axiomatic design (MU-FAD) was used to confirm the suggested model results. The study also conducted a system-based real case application in order to revealing the existing shortfalls of ISM Code implementation. The study was also conducted real case analysis, which was propeller shaft misalignment failure. As the study conclusion pointed out that adoptations of ISO

9001:2000 quality standards in ISM Code provides invaluable benefits regarding to the technical management, improving the service quality and enhancing customer satisfaction in the shipping industry.

Knudsen & Hassler (2011) conducted a study that based on the conflictive findings between accident rates in shipping and IMO implementations. The study criticizes specific deficiencies that should be dispersing in order to attain safer shipping transportation. The study pointed out three main reasons that undermined IMO implementation regulations; shortage of time in combination with complex regulations, local differences, idiosyncrasies in port inspection procedures. The study conclusion emphasised that catastrophic accidents generate political pressure, so that, IMO enlarges its legislative framework without sufficient consideration. This might be good on paper and for the IMO' public image but the implementation compliance has to be verified before they entry into force.

Karahalios et al. (2011) proposed a system that intended to evaluate the implementation performance of a regulation in accordance with cost and benefits that might be generated from them. The study argues that new regulations might cause conflict among interested parties therefore, convincing the interested parties have always been a great issue especially considering shipping transportation, as a global industry. The study critiques the Formal Safety Assessment (FSA) due to it's not take any particular stakeholders' view and it's not specify who would have to pay for implementation of risk control options. From this perspective, the study suggests that regulations should be evaluated in accordance with financial, customer, learn and growth, and internal business perspective separately. In order to that, the study used the combination of the Balanced Scorecard (BSC), the Analytical Hierarchy Process (AHP) and the fuzzy set theory.

Schinas & Stefanakos (2012) proposed a methodological framework for prediction of the cost in which the environmental regulation might cause to increase of the operating expenses of merchant ships. The study investigated the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, regulations for the prevention of Air Pollution from ships. The study grounded on the Stochastic Linear Programming (SLP) and supposed that ship operated in the Emission Control Areas (ECAs) and non-ECA areas, separately. Generally, the study compared operational costs with operational benefits.

Karahalios et al. (2014) proposed an assessment methodology, which based on System of Hierarchical Scorecards (SHS), to measure the implementation costs and benefits of a newly introduced or existing maritime regulation according with the ship operators' perspective. The proposed methodology consists of AHP and the fuzzy set theory. Moreover, the study enables ship operators to evaluate their performance via SHS so they can improve their implementation performance. The study emphasizes importance of the Information Technology (IT) since; it can be used to collect the information even daily basis for the evaluation of the ships, departments, and companies. The study result concluded that regulators could use the proposed methodology to justify their decisions. Because of its flexible structure, the model is applicable for many other industries, to illustrate, nuclear plants, aviation, petrochemical plants.

Bhattacharya (2012) conducted a qualitative analysis to determine the employment and social conditions support or not the effective implementation of self-regulation, which was brought in shipping industry by the ISM Code in 1998. The study findings clearly demonstrate that there are huge gap between managers and seafarers perspective about the Code implementation. The other important cause that undermines the ISM Code effectiveness is lack of seafarers' participation in management of workplace health and safety. According to the study conclusion, without seafarer's participations, the Code objectives mostly failed, thus it will not be effective.

Vanem & Skjong (2006) conducted an achieved study, which supported by the FIRE EXIT project, generated a set of well-defined evacuation scenario for the use in advanced evacuation analysis of passenger ships with regard to current maritime safety regulations. Regarding IMO regulations, passenger ships are required to evaluate by two different methods; simplified evacuation analysis or an advanced evacuation analysis. Recent developments of ship design and navigational aid equipment's has lead to carrying several thousand people in ones, therefore, applying advanced evacuation analysis is necessity. For this reason, advanced ship evacuation simulation software should be used to improve passenger and crew safety on board ships. According to the study conclusion, the suggested scenarios by IMO regulations are not adequate for the representing any particular hazard. It is a big challenge to map into real case these evacuation scenarios. However, the study

proposed a new set of evacuation scenarios, used in advanced evacuation simulations.

Schröder-Hinrichs et al. (2013) analyzed the documents that proposed by Maritime Safety Committee (MSC) to assess the ‘mechanisms’ of decision-making and the priorities for setting the agenda in MSC regarding maritime human factors. The study keynoted that the human element is a permanent factor that has been contributed to marine accidents, in spite of the technical and legislative improvements in shipping industry. Human factor related regulations have been entered into force after maritime accidents, so these regulations have reactive characteristic. Fortunately, IMO has changed its perspective that a number of examples of more recent regulations that can be considered as a proactive. Conclusion of the study pointed out that it is too early to confirm IMO has developed a proactive rule-making process.

The second chart of the literature review that study investigates is human factor. Shipping industry considered as a human system because from operations to regulations all component in shipping industry highly rely on human factors. Furthermore, studies confirmed that 80% or more major accidents are caused by the human elements in shipping industry. Therefore, investigating the human element role in this complex system is vital. The human element also provides great opportunity to prevent the majority accidents in sea-born transportation. Thereby, this thesis take close looks on this important manner so as to presents the course of the recently published literature about the human element.

Hee et al. (1999) developed a methodology, which was the Safety Management Assessment System (SMAS) that evaluates human and organizations factors in maritime. The study defined the SMAS as a screening method that selects and trains operators of the system to conduct a self-assessment. The study argued the five attributes of the highly reliability organizations and considered these attributes are the first step the reducing the marine accidents. These attributes are process auditing, appropriate reward systems, high standards of quality, appropriate risk perception, and command and control functions. The study conclusion stated that SMAS provides more accurate result than the randomness so it is better the use the SMAS methodology for the human and organization evaluation in shipping industry.

Hetherington et al. (2006) conducted retrospective research that investigated maritime literature on safety in three key areas: common themes of accidents, the influence of human error, and interventions in order to reveal the human element role in shipping industry. The study examined 20 studies that investigated maritime accidents caused by seafarers. Fatigue, stress, health, situation awareness, teamwork, decision-making, communication, automation, and safety culture is considered considered main reason these accidents, therefore they have important effect on the maritime accidents. The study conclusion also argued that maritime work envirimentalso has positive effect on maritime accidents, for example; the inability of employees to leave the worksite, extreme weather conditions, long periods away from home, and motion of the workplace.

Celik and Er (2007) conducted a research that investigated the potential role of the design-based failures in shipboard systems on human errors during the operational process. The research initially examined statistical studies that not only universal but also regional in order to gain a comprehensive viewpoint on the maritime accidents.

Moreover, the study mentioned several human error model and framework and demonstrated their taxonomies on human error. Among these models, the study took advantage from HFACS because of its comprehensive perspective. The influences of lacking of ergonomics requirements, maintainability, and integration of technology and automation into systems onboard ships were also examined deeply. Therefore, the roles of poor system design and constructional failures on human error clearly identified in the study conclusion section.

Celik & Cebi (2009) conducted an exploring study that intended to identification of the human elements role in shipping accidents. The study mainly based on both HFACS methodology, and Fuzzy Analytical Hierarchy Process (FAHP). Thus, the study enables to quantitative analysis on human error in order to increase the consistency of model outcomes. The study evaluated maritime accidents with regard to HFACS' four level. According to the study conclusion, skill-based errors are the prior causes at the first level (unsafe act). The lack of preconditions, especially in personnel related factors such as coordination, communication, and planning is dominant cause at the second level. Inadequate supervision level contains inadequate crew potential, disorganization in maintenance planning, and management processes.

Poor management in organizational processes especially in shipboard maintenance and organizational climate is considered primarily cause at the final step.

Akhtar & Utne (2014) conducted a research, which based on Bayesian Network (BN) modeling; investigated human fatigue in the bridge management team and the risk of ship grounding. HFACS model also used in the study in order to revealed the latent factors, which often result in fatigue. The study pointed out that fatigue is the most encountered cause that lead to accidents. It underlined the fact that the human fatigue is difficult to measure; thereby, statistical reports and accident investigation reports usually underestimate its role in the maritime accidents. Study conclusion clearly demonstrates that human fatigue strongly effects grounding and other maritime accidents. Other human related factors were also deeply analyzed in order to clarify the human factors role in the maritime accidents.

Chauvin et al. (2013) analyzed 27 collisions in maritime transportation to find out the related human and organizational factors, which might lead to these accidents. The data used in the investigation had been gathered from Marine Accident and Investigation Branch (MAIB) and the Transportation Safety Board (TSB). The analysis mainly based on HFACS model; which derived from Swiss Cheese Model (SCW). The results of the analysis indicate that decision errors have privileged effects on the collision accidents. Considering the pre-condition of the unsafe act; as a second level of the HFACS model, poor visibility and misuse of instruments (environmental factors), loss of situation awareness or deficit of attention (conditions of operators), deficits in inter ship communications or Bridge Resource Management (personnel factors) are some of the prominent causes. The study also highlighted the importance of the Bridge Resource Management (BRM).

Chen et al. (2013) proposed a new HFACS- MA methodology, which derived from both Systemic Occurrence Analysis Methodology (SOAM) and HFACS. The study reinforced the methodology with Generic Error Modelling System (GEMS), and SHEL model (Software (S), Hardware (H), Environment (E) and Liveware (L) to define and identify the contents of organizational and human errors. The study also extent HFACS model through add a new dimension on that, which is external factors. The study conclusion pointed out that comprehensive perspective should be gained on the human and organizational factor; since, accidents are resulted from more than one human error.

Bal et al. (2015) underlines the fact that fatigue has a great influence on maritime accidents. Therefore, the study utilized the AHP for the purpose of prioritize the fatigue causes. Along with the study, Lactate Test also conducted to measure fatigue levels of seafarers. In addition to SPSS software, Exploratory Data Analysis (EDA) was also employed in the study. According to the study results, seafarers' fatigue levels are high at most of times, especially during the port calls.

Technological and mechanical perspective is one of the most critical components that effect maritime safety. Maritime industry has witnessed great development considering the navigational aids and automatization technologies. However, some researchers and practitioners have argued this enhancement's effect on the other components in maritime industry. According to the publicized research, technological and mechanical failures are the primer components that cause the shipping accident followed by human factor. Consequently, the current study has investigated the several researches, which analyzed the technological aspect of the maritime industry.

Tzannatos (2005) investigated technical reliability of the Greek coastal passenger fleet in terms of the transport power, which imply that transport work per unit time, and specific reliability that refer to keep the fleet working at the higher level when the transport work demand increases (e.g. summer season). The study conclusion has outlined some specific conditions that should be taking into account to improve technical and mechanical reliability in shipping industry. To illustrate, design, construction, and lack of experience in start-up, control, monitoring and maintenance have led to operational failure especially in the new buildings ships. Further, the study conclusion revealed that engine room has a higher failure level that mainly affects the detrimental effects of high-cycle engine operation. Due to the high demand of the transport, summer season considered most critical period over the year. The study also emphasise that ships crew must be educated with respect to the new technological enhancement.

Eide et al. (2007) developed a model that intended to estimates risk level of the oil spill for the crude oil tankers. Due to its flexible design, the model might be extended to implement for the other types of ships as well. The model developed to implement at The Norwegian Coastal Administrations new Vardø VTS (Vessel Traffic Service) center as a decision support mechanism that helps decided to which

ships should be monitored closely. The model estimates the risk in terms of four selected maritime accidents type: powered grounding, fire and explosion, drift grounding, and collision, which are most encountered accidents in maritime domain. The study conclusion claimed that the impact of the oil spill not only related with the spill size, distance to shore, chemical composition of oil but also area's vulnerability; thus, the further studies should also take account this objective.

Lambrou et al. (2008) conducted a project that is called Intelligent Maritime Environment (i-MARE) based on information and communication technologies (ICT), aimed to improve maritime transportation security and cost efficiency and operational safety. The project verified on the short sea shipping business, yet it might be applied on the other operational area. The project took advantage from ambient-intelligence technologies and identified some key process areas: maritime regulations, rules compliance, and port operations, which these are important components of the maritime industry, so that they affect marine companies' competitiveness. The study conclusion argued that to achieve further improvements in shipping operations, to illustrate; increase operational safety, and efficiency, while, decrease the operation duration, and cost, innovative and collaborative mechanism is prior condition.

Vanem and Ellis (2010) developed a passenger monitoring system, which is a decision support system that helps the chief officer in emergencies in passenger ships. The study derived from the MarNIS project and based on the on RFID technology. Several accident investigation reports reveal that mustering, counting, controlling, and guiding passengers are extremely challenging for the crews member in an emergency situation; because, its generate stressful and intense work environment. Therefore, the project aimed to help crewmembers to determine passengers' location and exact number to guide them for reaching the safety areas. The monitoring system was evaluated in terms of the cost-effectiveness, as suggested by IMO in the FSA. The research conclusion founded out that the project was not cost effective; but, the study depend on several assumption, which are uncertain and used technology cost expected to decrease over the years; so the evaluation of the project should be updated in the forthcoming years.

LiPing et al. (2011) proposed an application based on video surveillance. The main objective is improved the navigational-aids inspection. The study clearly expresses

that the old mode navigational-aid disadvantages are; low reliability, poor real-time, low efficiency, high cost, and high risk, which these components are jeopardizes shipping companies' image straightly. However, video based surveillance inspection can save cost, time, while improving navigational safety, because, it can provide real time inspection. The study conclusions have confirmed that real time inspection of the navigational-aids is factional application for the saving cost, reducing the operational time, and increasing the operational safety in shipping industry.

Methodological background is relatively important manner particularly in the problematic area; because, problem solving is highly depend on the utilized methodological compatibility and competency with the inspected problem. Further, multifaceted problems required to be handling with the reliable, approved, and consistent method to provide optimal solution for all shareholders. From this viewpoint, the study examined numerous researches in the maritime literature in terms of the utilized methodologies in order to introduce current developments that maritime safety literature has been witnessed.

Rothblum (2000) discussed the statistical data, which gathered from the global and regional resources, to expose the human element role in the maritime accidents. The study underscored the fact that maritime transportation system is a human system; therefore, enhancement of maritime transportation safety is extremely relying on the human element. Statistical data clearly support the idea that ship structure and maritime system reliability has increased tremendously; even though, maritime accidents have not been reduced to the acceptable level. The study conclusion proposed that maritime industry should put the human element in the center to develop reliable and smooth operational capability to meet the shareholders' expectations.

Toffoli et al. (2005) analyzed 270 maritime accidents, which result from bad weather, in order to identify certain warning criteria for develop the standardized warning system against the environmental conditions. The study derived from MaxWave project that intended to improve exact and well-timed forecasting model. The study gathered the investigation reports from Lloyd's Marine Information Service and the time line is cover from 1995 to 1999. It also compered the ships characteristic that involved the accidents. It results indicated that the weather related

accidents occur when a ship operator was restrained from forecasting by the wavelength in particular when its reach half the ship length.

Lee et al. (2001) conducted a representative study on the Formal Safety Assessment (FSA), which examined the hatchway watertight integrity of bulk carriers. FSA adopted by IMO for the purpose of improve the maritime safety by using the integrated and systematic evaluation systems for the implementation of the new legislative framework. In general, FSA methodology is formed five sections: hazard identification; risk assessment; risk control options; cost–benefit assessment, and final recommendations. Moreover, problem description is the pre-request condition for the model. According to the study conclusions, 18 hazards are identified and 32 risk control measures are suggested to reduce the associated risks with the hatchway watertight integrity of bulk carriers.

Wang and Foinikis (2001) examined the containerships safety regarding the FSA framework in order to explore the weak points that need to be improved by the maritime executives and practitioners. The study challenge was gathering available and reliable data; because, intense competition in maritime industry makes companies reluctant to share their data and lack of the administrative audit for the data collection. The statistical data about the container shipping imply that container ships involved accidents had small part of the total volume of the maritime accidents, which was 7% at that time. Nevertheless, it mostly cause the cargo damages, personnel injuries, pollution, and ship structural failure, but rarely loss of the human lives. It claimed that shore oriented human error factors were the primal causes at the container shipping accidents. Its conclusion called attention to four critical areas to enhance container-shipping safety: container ship hull stresses, container ship fire-fighting and life-saving equipment, human element, information availability, reliability and interchange.

Wang (2002) investigated the offshore safety cases with respect to the FSA; thereby enhanced the FSA application with ship design and offshore industries. The study exemplifies three FSA applications on offshore safety in order to describe and discuss related approaches. It stated that only one assessment methodology is not appropriate to evaluation of the offshore or ship life cycle risks, so that, two or more methodological systems should be considered to apply with together. It also underlined the fact that mathematical approaches do not always appropriate to use in

the system assessment. However, novel decision-making techniques required to reliable numerical data related to defined problems. The study claimed that good design, training, and operation in an appropriate management system is key points that suppose to be enhancing to prevent the marine accidents.

Lois et al. (2004) conducted a research about the cruise ships in order to analyze its characteristics and suggest formal safety assessment for it. The study demonstrates a case study that verifies the suggested model. Carrying the thousands of people, cruise ships have been an attractive topic in the maritime safety literature. Therefore, cruise ships industry has relatively safety record compared with the other subbranch accidents in maritime industry. However, study conclusion asserted the fact that there are still some crucial gaps in operational safety; needed to be full in to minimize the probability of accidents. The human reliability, fire fighting, and people communication are the mentioned gaps in cruise shipping.

Trucco et al. (2008) proposed sophisticated risk assessment model based on the Bayesian Belief Network (BBN) in the maritime industry. The proposed model stemmed from the fault tree analysis in order to integrates human and organizational factors to conduct comprehensice risk analysis. The suggested model applied on collision accidents in maritime transportation and conducted a sensitivity analysis to confirm the model consistency. Moreover, the proposed model might be used for the cost and benefit analysis as suggested in FSA, which is required rulemaking process in maritime industry. The study argued that complex socio-technical systems' risk assessment need to be perform with an advanced tools to achieve deeper understanding of the system risk. Its conclusions claimed that the proposed model would lead to a significant reduction of the accident probability, if executive or related stakeholders utilized the systematic and reliable method, as indicated.

Zhang et al. (2013) conducted a research that aimed to enhance Yangtze River navigational safety by using the Bayesian network for the risk estimation. The study addressed the fact that FSA methodology usually conducted with qualitative risk estimation models, while quantitative risk estimation models are not used with in it. In order to develop a quantitative risk estimation model, the study conducted a Bayesian network case study on the inland waterway. For the first time, inland waterway safety was aimed to increase by taking account the accidents probability and consequences. It investigated 3180 accidents that happened the between 1986

and 2007, which included loss of many human lives, marine pollution, cargo and ship damages, for the hazard identification. More importantly, the model enables identification of the parameters and conditions that have the greatest impact on accident consequences.

Hänninen et al. (2014a) applied Bayesian belief network on the maritime safety management to develop an expert system to prevent maritime accidents and minimizing the related risk in marine traffic. Historical data and expert elicitation have been used to generate model factors. The suggested expert system is leading decision-support model that intended to enlarge maritime traffic safety through safety management. The study conclusion claims that Port State Control (PSC) inspections are effective preventive mechanism. It has increased the probability of the adequacy of the safety management almost twice. In parallel, PSC inspections data have been used for the exploring the interactions between the several types of deficiencies found on ships and ship's involvement in maritime traffic accidents and incidents by Hänninen et al. (2014b). The utilized data gathered from the Gulf of Finland Vessel Traffic Service incident reports that cover 2004–2008 years. It argued that PSC inspection based on the inspector observations that might be biased and uncertain, therefore, tools alike Bayesian network models need to be utilized excessively.

Sii et al. (2001) developed safety assessment model, which based on fuzzy logic, in order to evaluate the feasibility and concept design stages of the maritime and offshore systems. The study underlines the fact that conventional probabilistic risk assessment models are not suitable for some industry, where uncertainty situations are dominant. Maritime and offshore industries are using increasingly complex systems; therefore, these kinds of industries are required to apply the sophisticated scientific methodologies to evaluate their safety level. Using the qualitative oriented models such as, fuzzy set theory provides great advantage.

Balmat et al. (2009) conducted a project that aimed to develop a MARitime RiSk Assessment (MARISA) systems based on the fuzzy logic. The project mainly builds on the previous study, which approved the individual index that helps to rating the risk level of ship. Researchers believed that this index could be used in real time assessment. At this point, one of the most important objectives of the project is automatic detection of the high-risk ships. To obtain a risk factor for a ship, the study

take into account not only ships characteristics such as; ship's age, flag, and type but also environmental conditions that affects a ship safety significantly such as; sea state, wind speed, and visibility. Case studies on the bulk carrier, passenger, cargo and oil tanker have been conducted to verify the project. Moreover, Balmat et al. (2011) conducted another study, which also based on the MARISA, intended to risk assessment in terms of the pollution prevention from ships. Besides the ship characteristic and environmental conditions, the study takes into consideration ship speed and ship position.

Abou (2012) conducted a study that based on the intuitionistic fuzzy sets, which extended by the Dempster–Shafer theory, for the purpose of the monitor safety-critical systems performance in shipping industry. As a sample survey, the study examined the ship engine risk considering all related aspects. The study argued that the suggested methodology can be used for the uncovering the rational diagnosis decision-making rules. Even if the model used the holistic view of fault configuration effects, ship engine assessment is surpassing the scope of this study.

John et al. (2014) proposed a new methodological framework to evaluate the risk assessment of seaport operations. The fuzzy analytical hierarchy process, evidential reasoning (ER) approach, fuzzy set theory and expected utility were integrated to build a novel model; because, conventional risk assessment models are considered inadequate for the high uncertain operational environment. The study elaborately investigated seaport operations and diverse the related risk factor regarding the evidential reasoning approach.

2.2 Targeted Contributions to Literature

The current study contribute to literature at several points, first and foremost; it promoted the fire preventive model, which initially identify the fire related deficiency causes then prioritization these causes to elicit the root causes. Enabling to the take precautions against the fire related deficiencies before the undesirable events occurred, the suggested fire preventive model is considered as a proactive model. Keep in mind the fact that maritime regulations are usually enter into force after the accidents happend, contribution of the study in the maritime literature is invaluable.

The numerous studies express that the human factor has significant influence on the catastrophic accidents in shipping industry. Accident investigation report underlines this unexciting fact, as well. For this regard, several researches intended to investigate the human factor in shipping industry. Newertheless, current maritime accidents pointed out that the human element is still a complex component that needed to be investigated. The study contributes to the maritime safety literature investigates the human element related issues in fire safety with advanced, reliable, and constant metedologies, which have been a huge research gaps in it.

For the first time unique 72 causes have been determined for the presenting the fire related deficiencies in shipping industry. Moreover, these causes have been classified with respect to the HFACS framework. It is remarkable contribution to the maritime literature; it makes this study pioneer; detailed investigation of the fire deficiencies has been completed.

The study conducted a comprehensive literature survey that divided the published issues into four categories in order to facilitate the understanding the course of the current state of the maritime literature.

2.3 Targeted Contributions to Industry

Maritime industry has been suffered from catastrophic accidents in several ways, such as, loss of big amount of money, customer dissatisfaction, and loss of goodwill etc. To avoid these kind of mentioned loses; maritime industry is urgently in need of the feasible advanced scientific method in order to prevent occurrences the maritime accidents. Based on these facts, the study provide flexible advanced scientific fire preventive model, which helps shipping companies to minimize the accidents risk through elimination of the root causes. Moreover, proposed model might be used for a group of ships or even for fleet. Therefore, the contribution of the study in the maritime industry is admirable.

In addition, Maritime industry has been caused unfortunate events, which has led to environmental pollutions. After these kinds of events, authorized bodies implement the new legislative framework that intended to prevent re-occurrences the same accidents. However, this approach, named learned from accidents, is not appropriate for the prevention of the maritime accidents. At this point, the study contributes to

maritime industry in terms of the proactive risk management, which helps the shipping companies eliminate the accident causes before the accident happened.

3. METHODOLOGICAL BACKGROUND

3.1 Human Factor Analysis and Classification System (HFACS)

Originally, HFACS derived from Swiss Cheese Model by Reason (1990). It has been used for the analysis of human factor's contribution to catastrophic events, accidents, hazardous occurrences, and deficiencies in numerous industries. Generally, HFACS evaluates active failures and latent conditions along with the accidents in four levels. Active failures are sets of inappropriate actions that have immediate consequences, whereas, latent conditions deal with the different levels of organization. The four levels in the model are i) unsafe acts, ii) pre-conditions for unsafe acts, iii) unsafe supervision and iv) organization influences. Unsafe acts have been divided into two categories: violations and errors. On the one hand, violation can define as an intentionally conducted unsafe act, error implies the inappropriate skill, decision, perception about the situation. Precondition for unsafe acts characterizes as a broad category; these influenced environmental, operators, technological, and physical factors. Further, unsafe supervision refers to lack of administrative surveillance for the identified risk overall the system. Organizational influences are considered organizational climate and allocation of the resources effects on the accidents (Chauvin et al., 2013).

3.1.1 HFACS applications

Initially, HFACS utilized for the aviation accident investigation (Shappell and Wiegmann, 2000, 2001). HFACS model has gained immediate and constant attention from researchers and practitioners, as a result of the systematic and convincing proposed systematic investigation method. In the early years, HFACS model was successfully applied not only aviation by Shappell et al. (2007), but also in the railway industry (Reinach and Viale, 2006) and the mining industry (Patterson and Shappell, 2010). Moreover, Rothblum et al. (2002) study was the pioneer scientific research that aimed to investigate human factor in maritime accident. In order to accomplish a quantitative aspect, Celik and Cebi (2009) combined HFACS with fuzzy set theory in order to analyse single accident case with error distribution

in accordance with the operational evidences given in accident reports. Recently, Akyuz and Celik (2014a) used HFACS supported with cognitive mapping approach to confirm the dependencies between causation factors.

3.2 Fuzzy Cognitive Map (FCM)

Cognitive mapping has been considered as a causative representation of complex systems and can be used to model and manipulate the dynamic behavior of systems (Papakostas et al., 2008). Kosko (1986) improved the cognitive mapping through fuzzy logic and suggested the Fuzzy Cognitive Mapping. Taking advantage of the fuzzy logic and neural networks; fuzzy cognitive mapping has been suggested as a scientific method for making inferences in cases with substantial uncertainty, imprecision and vagueness (Vasantha Kandasamy and Smarandache, 2003; Tsadiras, 2008). Compared to expert systems, fuzzy cognitive maps (FCMs) are relatively quicker and easier to acquire knowledge (Papageorgiou and Stylios, 2008). Generally, the FCM models are organized by the way of expert knowledge and experience in the operation of the system. Questionnaire survey, documentary coding and interviews are some of the most popular ways for this sense. FCMs can be developed for a single expert or a group of experts, where the latter has the benefit of improving the reliability of the final model (Yaman and Polat, 2009). The aggregation of the fuzzy numbers from two and more experts is not required advanced mathematical knowledge, hence; it is considered a simple procedure (Stach et al. 2005). The interconnections are described by the each expert associated with linguistic variables (weights) which are later composed (e.g. by fuzzy arithmetic or defuzzification methods) to produce the combined map. For the purpose of the combining multiple FCM models into single one; several procedures have been proposed (see e.g. Kosko, 1992; Stylios and Groumpos, 2000).

A FCM can be represented either as a graph, consisting of concepts (e.g. entities, states, or characteristics of the system) and weighted interconnections between these concepts, or as an adjacency matrix, which has entries w_{ij} 's indicating the direct relationship between concept i and concept j . Figure 3.1 illustrates a simple FCM consisting of five concepts C_i ($i=1, \dots, 5$) where w_{ij} represents the influence degree from cause C_i to effect C_j . FCM does not allow any direct connections between a concept and itself, thus all w_{ii} elements equal to zero. All other

w_{ij} elements take values in $[-1, 1]$ and Papageorgiou (2011) explains the meaning of these values as;

- $w_{ij} > 0$ indicates a causal increase (i.e., C_j increases as C_i increases, and C_j decreases as C_i decreases)
- $w_{ij} < 0$ indicates causal decrease (i.e., C_j decreases as C_i increases, and C_j increases as C_i decreases)
- $w_{ij} = 0$ indicates no causality

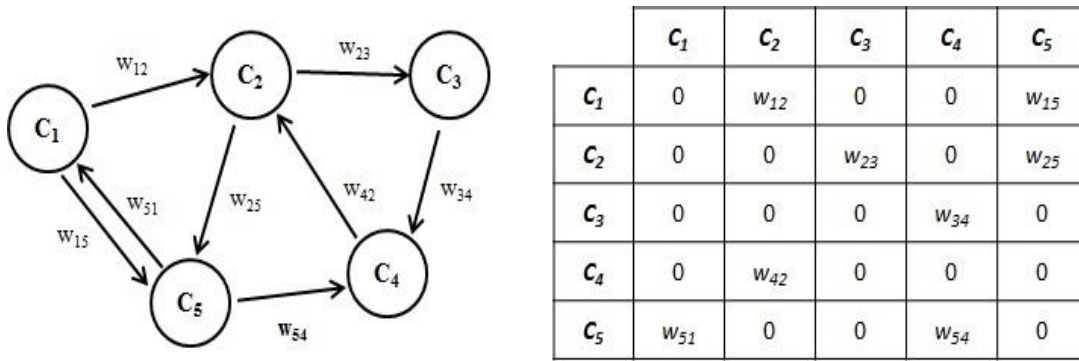


Figure 3.1: A hypothetical FCM model and the corresponding adjacency matrix.

Once the FCM is constructed it is used to perform qualitative simulations in order to predict possible changes and to observe whether the system converges toward a steady state. During the simulations a model can reach three possible states that are listed below (Kosko, 1997):

- A steady state where the output values are stabilizing at fixed numerical values
- A limit cycle behavior where the concept values are falling in a loop
- A chaotic behaviour where concept values wanders forever without apparent structure or order

A more formal definition of the iterative procedure can be described as follows. The FCM should be first initialized. In other words, the activation level of each concept takes a value based on expert opinion about its current state or measurements from the real system. Let

each concept take its initial value as $A_i^{(t)}$, where A_i is the value of concept i at step t , and simulated iteratively. Then the value of each concept in an iteration is calculated as (Papageorgiou et al., 2009)

$$A_i^{(t+1)} = f \left(A_i^{(t)} + \sum_{\substack{j=1 \\ j \neq i}}^n A_j^{(t)} w_{ji} \right) \quad (3.1)$$

In Eq. (3.1), $A_i^{(t+1)}$ is the value of concept at step $(t+1)$, $A_i^{(t)}$ is the value of concept at step (t) , w_{ji} is the weight of interconnection between C_j and C_i . f is the threshold function that reduces the result of the multiplication into a normalized range (within $[0, 1]$ or $[-1, 1]$). The most common activation functions are (Tsadiras, 2008): bivalent, trivalent, sigmoid, hyperbolic tangent.

3.2.1 FCM applications

FCM have been successfully applied in a variety of scientific areas, such as; Stylios and Groumpos (2000) applied FCMs on the supervisory control systems. They analyzed the capability and usefulness of the FCM through a case study on the heat exchanger systems. Further, Stylios et al., (1997) executed research on the distributed systems and control problem; they investigated a novel hybrid fuzzy neural system. Tsadiras et al., (2003) introduced the FCMs on the decision support systems for political decisions. The study incorporated ideas from Artificial Neural Networks and Fuzzy Logic. Craiger et al., (1996) applied FCMs on the organizational behavior. Papageorgiou, (2011) conducted a FCM based research that investigated decision in medical informatics. The study proposed a dynamic decision support system and applied the proposed model upon the selection of the radiotherapy treatment planning. Nasserzadeh et al., (2008) utilized the FCM on marketing in order to clarifying the factors that affect the customer satisfaction in banking industry. Lazzerini and Mkrtchyan (2011) take advanted of the extended fuzzy cognitive maps for the risk analysis in Software Project Management (SPM).

3.3 Model Development

The suggested model that named HFACS-FCM model is involved with Fuzzy Cognitive Mapping (FCM) and Human Factors Analysis and Classification System (HFACS). The further sections introduce the suggested model.

3.3.1 Conceptualizing

A new comprehensive framework on fire safety related deficiency analysis is presented under this sub-section. The proposed deficiency analysis model has been visualized in Figure 3.2. The model main purposes are to root cause identification, prioritization, and generate the preventive action to eliminate root causes. The model utilized several resources to gather the reliable data, to illustrate; PSC inspections reports, company audits reports, near-miss reports, hazardous occurrences reports, accident reports, and vetting surveys reports are some of them. Gathered deficiency database are classified with respect to the HFACS logic. After that, FCM model underline the relationships among the potential root causes of the fire related deficiencies on board ships. Moreover, conducted simulations are helped the clarify the root causes. Finally, the integration phase enables preventive action adaptation into ship operational level.

3.3.2 Fuzzy cognitive application stages

In order to demonstrate the suggested model, application stages consist of the detailed information about the fuzzy stages. Firstly, the application begins with the data gathered from the several resources to identification of causes of fire related deficiencies. Then, questionnaire surveys with linguistic variables utilize to identification of the casual relationships. Next, Max/Sum method is used to aggregation of weights from multiple experts. In order to defuzzification, the model takes advantage of the center of gravity method. After this point, analysis of direct relationships; analysis of indirect relationships; inference through qualitative simulations are used for the decided to final list of root causes (see Figure 3.3).

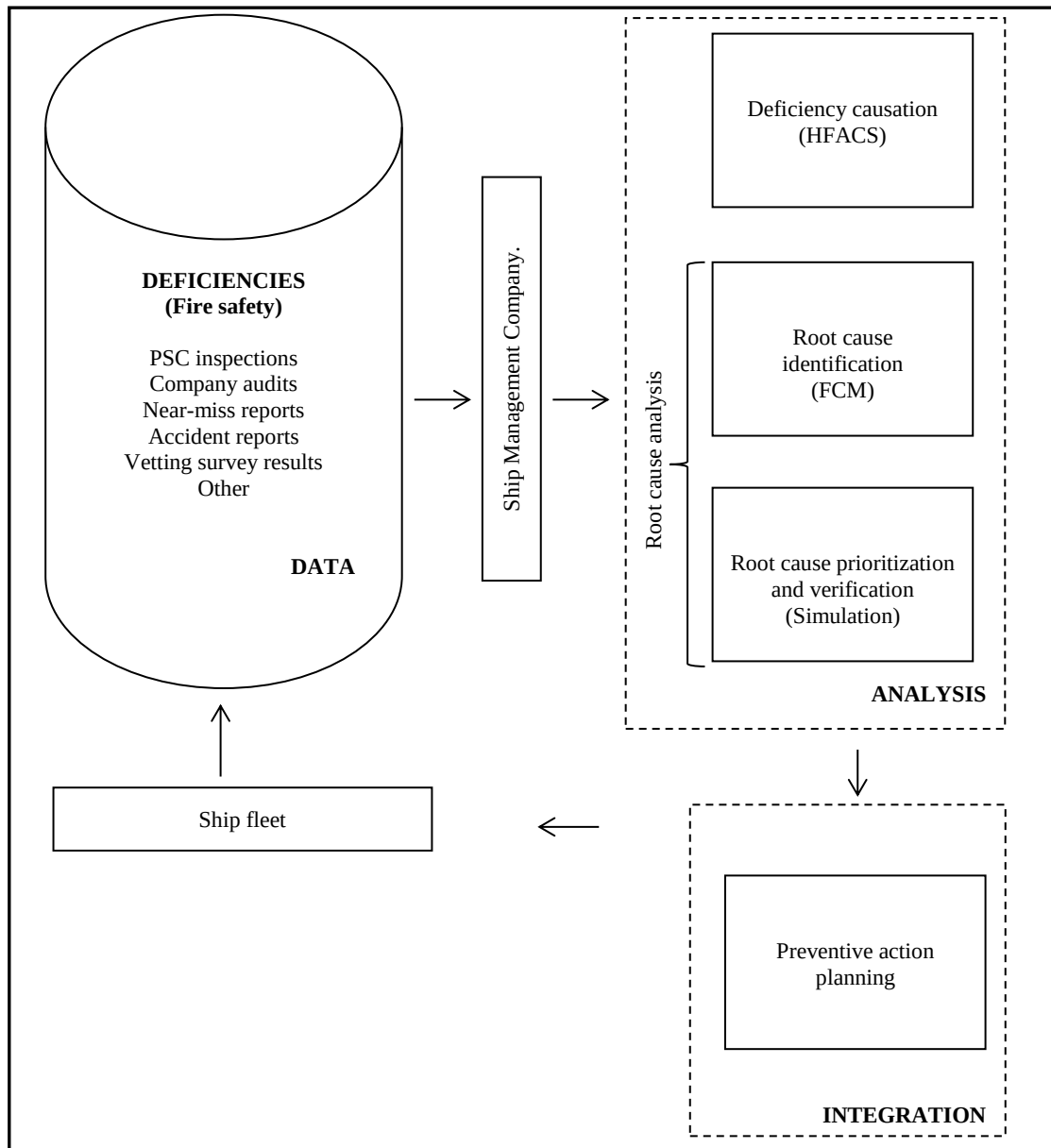


Figure 3.2: Conceptual framework of the model.

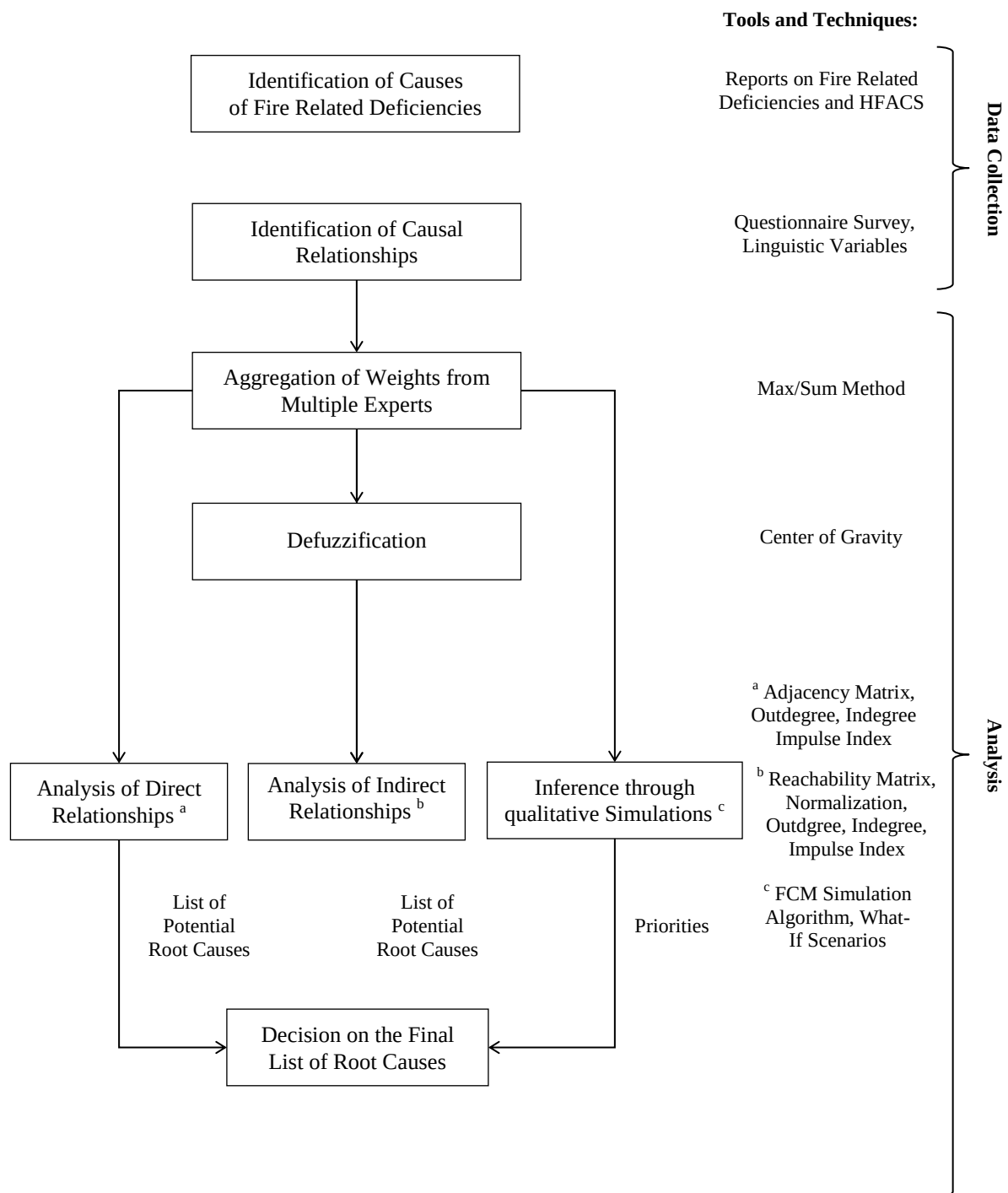


Figure 3.3: The flow of the proposed FCM methodology.

Step 1: Identification of causal relationships

As previously explained, the causes (i.e. concepts in the fuzzy cognitive map) are identified by reviewing diverse reports on fire related deficiencies and employing the human error

framework HFACS. In this step, the causal relationships between concepts are identified by providing domain experts ordered pairs of concepts in a questionnaire format. This allows systematic examination of all relationships. Here, a causal relationship is characterized with vagueness, since it represents the influence of one qualitative concept on another one and will be determined using linguistic terms (Papageorgiou and Stylios, 2008). In this way, an expert transforms his knowledge and experience on the behaviour of the system into a fuzzy weighted graph.

The linguistic variable used in this study, expressing the degree of the causal relationship between two concepts, takes values in the universe $U=[0,1]$ and consists of the term set {does not affect at all (N), affects weakly in a positive way (W), affects weakly-moderately in a positive way (WM), affects moderately in a positive way (M), affects moderately-strongly in a positive way (MS), affects strongly in a positive way (S)}. Using these six linguistic terms, an expert can describe in detail the influence of one concept on another and can discern between different degrees of influence. Figure 3.4 depicts the membership functions of the fuzzy sets that are used to characterize these terms.

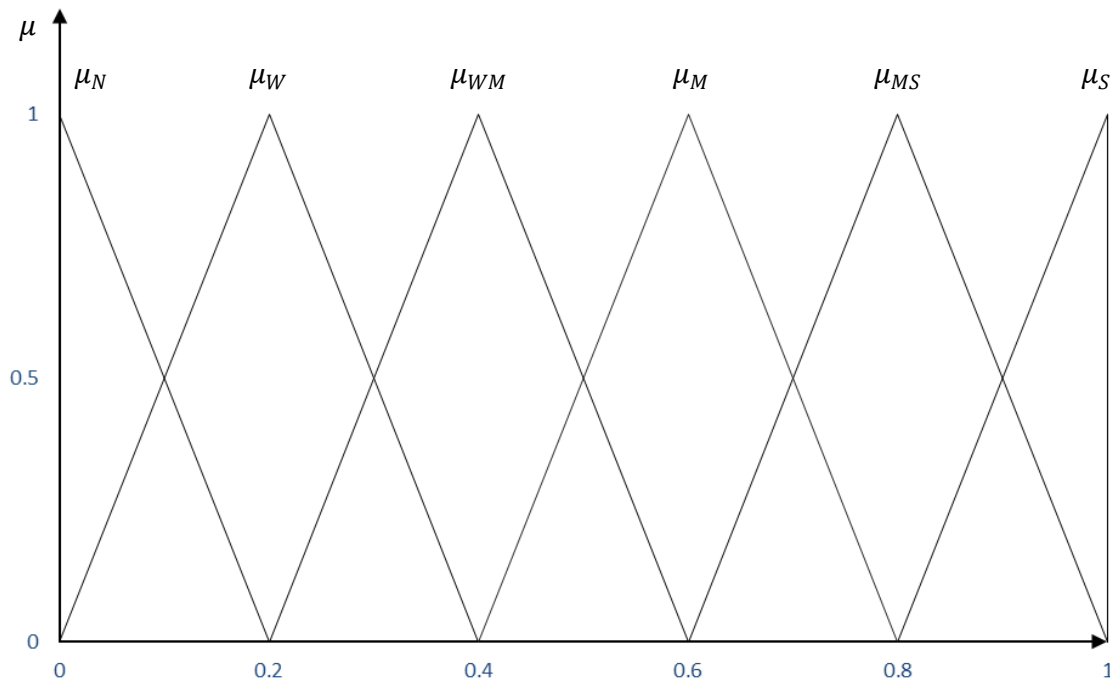


Figure 3.4: The membership functions describing the linguistic terms.

Step 2: Aggregation of individual weights and defuzzification

In order to improve the reliability of the final model, a group map is developed. The weights obtained from multiple experts are combined to produce the overall linguistic weights and the group adjacency matrix. The well-known SUM or MAX methods in fuzzy logic can be employed for this purpose. Figure 3.5 provides an example of the MAX operation where the two linguistic terms “moderately-strongly” and “strongly” are aggregated. If the experts have different priorities of importance, the different influences are reflected in the results through multiplying the membership function μ suggested by the k th expert by the corresponding credibility weight (Stylios and Groumpos, 2004; Saaty, 2004).

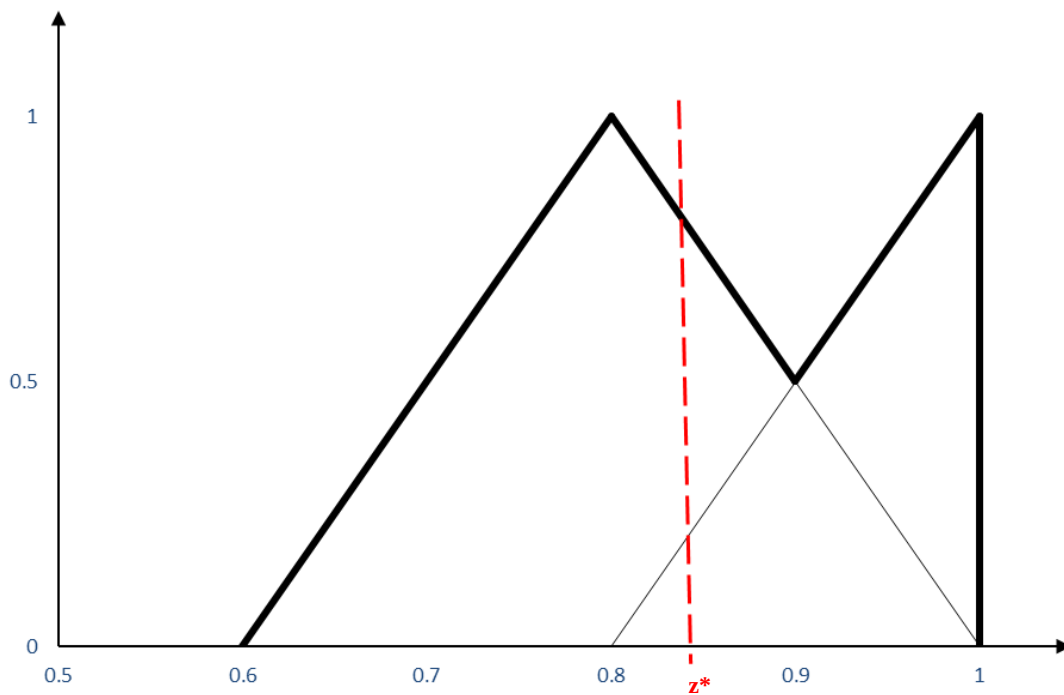


Figure 3.5: MAX method and CoG.

Once the overall linguistic weights are obtained, they are transformed to numerical (crisp) values using the Center of Gravity (CoG) defuzzification method. CoG is computed from the following equation (Ross, 2004):

$$z^* = \frac{\int \mu_{\tilde{w}_{ij}}(z) z dz}{\int \mu_{\tilde{w}_{ij}}(z) dz} \quad (3.2)$$

where $\int$ denotes an algebraic integration. The transformed numerical values will be within the range $[0, 1]$. The same procedure is applied to all the causal relationships among the n concepts of the map.

Step 3: Identification of potential root causes (Analysis of direct relationships)

As we aim to identify root causes (i.e. initial causes in a causal map), the role of each concept in the map needs to be carefully examined. An adjacency matrix W allows analysing the contribution of a concept in the map and articulates how this concept is connected directly to other concepts (Kosko, 1986). Each variable is defined by its outdegree (od) and indegree (id). Outdegree shows the cumulative strengths of connections exiting the concept and is expressed as the row sum of absolute weights of a concept in the adjacency matrix (Nozicka et al. 1976; Özesmi and Özesmi, 2004).

$$od(i) = \sum_{j=1}^n |w_{ji}| \quad (3.3)$$

On the other hand, indegree shows the cumulative strength of connections entering the concept and is expressed as the column sum of absolute weights of a concept in the adjacency matrix (Nozicka et al. 1976; Özesmi and Özesmi, 2004)

$$id(i) = \sum_{j=1}^n |w_{ij}| \quad (3.4)$$

Thus, a concept (i.e. a cause) that is less affected by the rest of the causal system than it has impact on it can be characterized as a potential root cause. To identify the role of variables in a complex system different criteria or rules have been proposed in the literature (Godet, 1994; Gausemeier et al. 1996; Asan et al. 2004). Here, the rules defined by Asan et al. (2004) are adapted to the root cause identification problem. Thus, a root cause i should fulfil the following rules

$$od(i) \geq \bar{x}_{od} \quad (3.5a)$$

$$IPI_i \geq 2 \quad (3.5b)$$

where $\bar{x}_{od}$ denotes the average outdegree taken over the entire concept set and IPI_i denotes the so called Impulse Index which is calculated for each concept i as follows

$$IPI_i = \frac{od(i)}{id(i)} \quad (3.6)$$

The maximum range of IPI_i extends from 0 (no influence on the system) to ∞ where the concept is not influenced by other concepts, but has an impact on others.

Step 4: Identification of potential root causes (Analysis of indirect relationships)

Examining the adjacency matrix reveals only potential root causes based on the direct relationships between concepts which are represented by causal chains of length one. However, this is not enough to reveal the hidden root causes which sometimes greatly influence the problem under study. Therefore, the diffusion of causal impacts through reaction paths and loops needs also to be considered (Godet, 1994; Serdarasan and Asan, 2007). These indirect relationships, which are represented by causal chains of length greater than one, can be revealed by raising the adjacency matrix to successive powers. The raw and column sums of each resulting matrix (raised to a certain power) are normalized to enable a comparison among the results of successive powers. The normalization originally developed in this paper can be expressed as follows

$$Nod(i)^q = \frac{\max_{i=1\dots n} \{od(i)\} \cdot od(i)^q}{\max_{i=1\dots n} \{od(i)^q\}} \quad (3.7)$$

$$Nid(i)^q = \frac{\max_{i=1\dots n} \{id(i)\} \cdot id(i)^q}{\max_{i=1\dots n} \{id(i)^q\}} \quad (3.8)$$

where $Nod(i)^q$ and $Nid(i)^q$ denote the normalized outdegree and indegree values of concept i for the adjacency matrix raised to the q^{th} power, respectively; and $od(i)^q$ and $id(i)^q$ denote the outdegree and indegree values of concept i for the adjacency matrix raised to the q^{th} power, respectively. Thus, the total outdegree and indegree values of concept i can be calculated by the following expressions

$$Rod(i) = (od(i) + Nod(i)^2 + \dots + Nod(i)^{n-1})/Q = \left(\sum_{q=1}^Q Nod(i)^q \right) / Q \quad (3.9)$$

$$Rid(i) = (id(i) + Nid(i)^2 + \dots + Nid(i)^{n-1})/Q = \left(\sum_{q=1}^Q Nid(i)^q \right) / Q \quad (3.10)$$

where $Rod(i)$ and $Rid(i)$ denotes the total outdegree and total indegree of concept i , respectively and indicate the reachability of concept i . In fact, the multiplication process continues until the adjacency matrix is raised to a certain power (Q) in which the concepts' order proves to be stable (for more detail see Godet, 1994). The resulting indicators are used to reveal potential root causes which might be assumed to be unimportant in the previous analysis but play a leading role because of indirect relationships. For this purpose the concepts are examined according to the same rules described in Step 3.

Step 5: Inference through qualitative simulations

Once the direct and indirect relationships are examined, the fuzzy cognitive map is used to perform qualitative simulations to capture the transmission of influence along all paths and to observe whether the system converges toward a steady state. From the steady state calculation we can get an idea of the ranking and thereby of the overall priorities of the variables in relation to each other (Özesmi and Özesmi, 2004).

The simulation process is initialized through assigning a value in $[0, 1]$ to the activation level of each concept, based on experts' opinion about a certain state. The value of zero indicates that a given concept is not present in the system at a particular iteration, while the value of one suggests that a given concept is present to its maximum degree (Papageorgiou and Kontogianni, 2012). In a particular iteration, the value of each concept is determined by its previous value and the preceding values of all concepts that exert influence on it through non-zero relationships (Papageorgiou, 2011). This iterative process does not produce exact numerical values; instead it allows analysing the dynamic behavior of the system.

The FCM simulation algorithm originally developed by (Kosko, 1988) utilizing Eq. (3.1) consists of the following five stages (Papageorgiou and Kontogianni, 2012):

- Stage 1. Define the initial vector A

- Stage 2. Multiply the initial vector A and the matrix W
- Stage 3. Update the resultant vector A at time step $t+1$
- Stage 4. Consider the new vector $A^{(t+1)}$ as the initial vector in the next iteration
- Stage 5. Steps 2 to 4 are repeated until $A^{(t+1)} - A^{(t)} \leq e = 0.001$ (where e is a residual describing the minimum error difference among the subsequent concepts) or $A^{(t+1)} = A^{(t)}$. $A^{(t)}$ will be the final vector.

Note that the iterative method applied here is not necessarily concerned about the structure, but the outcome, or inference of the map (Özesmi and Özesmi, 2004).

In order to prioritize the potential root causes, identified in Step 3 and 4, simulations are performed for different initial state vectors. In each “what-if” scenario, only one particular concept (i.e. cause) is activated by assigning a value of one to its activation level. In this way, it is possible to observe the changes in the activation levels of other concepts throughout the simulation. The higher the number of concepts influenced (i.e. activated) in the early iterations by a particular concept, the more likely the concept is a root cause.

Consequently, the decision on the final list of root causes is made by synthesizing the results of Step 3, 4 and 5. A case study on a set of fire related deficiency data is conducted in Section 5.

4. TECHNICAL BACKGROUND

Under this section, the study has aimed to give some brief information about the technical background of the fire safety on board ships. The section begins with the overview of the fire related accidents at sea, and continues with fire prevention on board ships. Next, regulations and procedural aspect of the fire safety at maritime industry broadly examined. Further, fire fighting drills and training are also examined in this section.

4.1 Overview of Fire Related Accidents at Sea

Fire related accidents at sea might be catastrophic; therefore, many researchers and maritime experts examine thoroughly the fire accidents for the purpose of prevent them or reduce damages, which they can make. According to the European Maritime Safety Agency (EMSA) annual maritime accidents review, fires/explosions related accidents have increased in 2010 relative to 2009 (EMSA, 2010). Moreover, Safety and Shipping review 2013, which conducted by Allianz Global Corporate & Specialty (AGCS), emphasize the fact that the one of most common causes of total loss was Fire/Explosion that 10% (AGCS, 2013). Another important statistic report that highlights the fire/explosion accidents is Finnish Annual Maritime Safety Review 2013, which pointed out that fire/explosion accidents comprehend about the 10 % of total accidents in the in Finland's territorial waters the period of 2002–2012 (TraFi, 2013). Beyond that, 15 Years of Shipping Accidents report clearly demonstrates that fire/explosion related accidents is one of the most contributing accidents type that causes the total losses during the period of 1997-2011 (Butt et al. 2013). All of these published reports implicate that fire related accidents have to be examined with advanced methods in order to prevent or reduce the fire accidents harm.

4.2 Fire Prevention on board Ships

Fire on board ships is considered one of the most dangerous situations for crews' safety and the carried goods. In order to prevent the fire accidents, some effective measures have been taking in to account for these bases. Particularly, detection and alarm unit, execution system and extinguishing system are advanced fire prevention tools that help practitioners to reduce the occurrences of the fire accidents (Li et al. 2013). Detection units are programed to detect fire and alert people against the fire accidents. Early respons are considered vital; therefore, it is very important to detect fire when it is at initial stages. Some researchers have investigated this delicate matter; Qiang (2011) conducted a researct that aimed to detection time estimation methods of fire detectors, while Wong and Fong (2014) executed an experimental study that investigates video fire detection and its application. Moreover, fire execution system and extinguishing system have unique consideration in this context, so that it have been examined detailed. Koshiba et al. (2015) conducted a research that investigated fire-extinguishing properties whereas, Liang et al. (2015) conducted a research about the probability distribution of pool fire extinguishing times using water mist. Further, Xiaomeng et al (2006) conducted a research that aimed to improve the water mist's fire-extinguishing efficiency with MC additive.

According to the Taylor (1996), firefighting might be divided into three stages; detection, alarm, and control. Detection is the first stage of fire firefighting that it can enable to bring the fire under control without serious damage, only if the fire detected its early phases. Therefore, to detect a fire as soon as possible is vital for firefighting MTAB et al. (1994). Once a fire is detected, it is urgently needed to give an alarm to warn other co-workers and take necessity action for firefighting or make decisions that situation require (i.e. evacuation). In order to take under the control of fires on board ships, two different kind of equipments can be used; portable extinguishers and fixed installations. The portable extinguishers might be beneficial for the relatively small size fires, which can be rapidly extinguished, whereas fixed installations is used at the more dangerous situation that might require to evacuation the regions where the fire set out (Taylor, 1996).

Soda-acid, foam, dry powder, and carbon dioxide are four main categories for the portable extinguishers, which can be found on ships. Soda-acid extinguishers are

generally located at the accommodation areas and used for the Class A fires. The tubes of the soda-acid extinguishers contain a sodium bicarbonate solution and because of the reactions that it's involved carbon dioxide gas are nascent. Foam extinguishers might be can be found two different forms MTAB et al. (1994). First, the main containers fill in sodium bicarbonate and inner container aluminium sulphate (chemical foam). The second, the main containers is filled with water and inner container carbon dioxide and foam solution (mechanical foam). On the other hand, carbon dioxide is kept under the high pressure in the carbon dioxide extinguishers as a liquid. Carbon dioxide extinguishers mainly located at the machinery space, and near electrical equipment for the fight with the Class B and C fires. Although, dry powder extinguisher is utilized on all class of fire; it mainly is inserted at the machinery space and near the electrical equipment. Dry powder extinguisher' has no cooling effect; therefore this considered its main drawback (Taylor, 1996).

Fixed firefighting installation on ships might be different from ships to ships and even some of them specifically designed for certain types of ships (Taylor, 1996). However, most ships have some common kind of fixed installations, to illustrate; fire main, automatic water spray, foam systems, carbon dioxide flooding, and inert gas. There are several pumps, which their capacity and size is stated under the related legislations, located in the engine room in order to provide the sea water to firefighting. However, an emergency fire pump is located another place than machinery space and its power also supplied independently MTAB et al. (1994). The automatic spray or sprinkler system utilizes throughout the protected areas, such as; accommodation areas, and machinery spaces. Moreover, the foam systems are also beneficial at the protected areas. Generally, mechanical foam is used in this system (Taylor, 1996). On the other hand, carbon dioxide flooding system is aimed to remove the oxygen in the fire related areas on the purpose of extinguishing the fire. Inert gases are identified by its ineffectiveness on the combustion, for instance; nitrogen and carbon dioxide. Burning fuel and cleaning exhaust gases are main resources of the fire extinguishing gas.

House (2004) conducted detail firefighting study that enlightens the required items that ships have to comply with. This notable information is briefly presented in this study.

Fire main and water service pipes should fit with hydrants and they are allowed to connecting only washing down. It is also important that the hydrants should be easily accessible. In order to ensure the two jets of water can bring to bear to any part of the ship, appliances should have sufficient MTAB et al. (1994). Cargo vessels, which has capacity 1000 grt and above, should keep two (2) self-reliant fire pumps and an emergency pump. Moreover, a passenger ship that over 4000 grt must hold three (3) fire pumps. Each fire pump capacity should be not less than 80% of the total required capacity, while the capacity of the emergency fire pump is not less than 40% of the total fire pump capacity MTAB et al. (1994). Hydrants' number and position should be complying with the required regulations and the pressure on the each hydrant should also be kept under the control, which the hose can be effectively handled. Isolation valves should capable of the separate the main fire pumps from the rest of the fire main. Fire hoses should be manufactured non-perishable material and should provide one (1) hose for each 30 meters. Nozzles have to provide dual purpose (i.e. spray/jet). A vessel, which over the 1000 grt, must have five (5) fire extinguishers in accommodation areas MTAB et al. (1994). Fire detection and alarm system should be supplied two independent source of power and its control panel should be located in the navigation bridge. It's also critical that they could be manageable by manually. All ships must have a fire control plan and its copy should be kept by shore side firefighting personnel. Over the 500 grt all ships must have international shore connection (House, 2004).

4.3 Regulations and Procedural Aspects

In order to prevent fire accidents on ships, there are several important regulations and codes developed and implemented by International Maritime Organization (IMO) that intended to improve fire safety on board ships. Firstly, International Convention for the Safety of Life at Sea (SOLAS), 1974, implemented to combine not only technological advances in fire detection and extinction but also lessons learned from fire incidents over the years in shipping industry (SOLAS, 1974). Moreover, Fire Safety Systems (FSS) Code implemented in 2001 under the SOLAS convention in an attempt to provide specific standards of fire prevention (IMO, 2007). Fire Test Procedures (FTP Code) also implemented to standardize the fire test procedures on shippin industry in 1998 (FTP, 1998).

4.4 Fire Fighting Drills

Fire drills prescribed in the Safety of Life at Sea (SOLAS) under the regulations III/19.3, III/19.5 and additional requirements for passenger ships III/30 in 1974 (SOLAS, 1974). The regulations provide required guidance and instructions to help conduct proper fire drills. In recent years, maritime industry has witnessed several catastrophic fire accidents that could have prevented if fire drills conducted properly. Fire drills have several significant benefits, to illustrate; crews gain familiarization in use of the firefighting equipment and in cooperation. Moreover, firefighting equipment is checked during the drill; the equipment is placed with respect to the firefighting plan and in good working conditions or not (DMA, 2002). On the other hand, several critical issues should be considered before the implementation of the fire drills. Fire drills must be safe so that, unnecessary risks should be left out and drills must be constructed according to firefighting plan. Fire drills frequency is determined by the related regulation thus, extended the drill frequency might have positive affect over the crews' familiarizations (DMA, 2002). However, fire drills shall be conducted with respect to the crews resting hours and should not result from fatigue. Next, fire drills' one of the important purposes is to enhance the crews learning, therefore the drills should be conducted at a safe speed so that, crews can gain familiarization their duties and with the equipment. Further, fire drills might cause serious accidents, so there are some delicate points that should be taking into consideration (DMA, 2002). i) Watertight doors should not be closed during the drills, because there might be a risk of persons getting jammed in the doors that are closing at great force. ii) The remote release of fire doors might cause a personal injury, thus before fire doors are remote released, crews should be warned. iii) Smoke might prevent the clear visibility so it can cause undesirable events, therefore crews should be informed (DMA, 2002). In order to properly handle the emergency situation on board ship, crew members should receive periodic training and drills. According to the SOLAS convention, each crew members should be participate in one fire drill within a month. A drill should conduct within the first 24 hours after a ship departure a port if only in previous month more than 25% of crew members would not participated on the drill. Moreover, crew members of passenger ships should participate weekly a fire drill. A fire drill should planned and conduct as if there are real emergency situation on board. During the fire drill, fireman's outfit and

other personal rescue equipment, the relevant communication equipment, the operation of watertight doors, fire doors and fire dampers, the necessary arrangements for subsequent abandoning of the ship should be checked.

4.5 Fire Training

Fire training minimum requirements determined in the Standards of Training Certification and Watchkeeping (STCW) under section A-VI /1-2 “Fire Prevention and Fire Fighting” and section A-VI /3 “Advanced Fire Fighting” (Nas and Peker, 2002). The code aim is to provide crews the essential knowledge and required competency to properly deal with fire on board ships. Thus, fire training significantly increases ships fire safety, while reduces probability of the catastrophic accidents caused by fire. STCW required specification of minimum standard of competence in fire prevention and firefighting are minimize the risk of fire and maintain a state of readiness to respond to emergency situations involving fire and fight and extinguish fires (STCW, 1995).

According to the STCW convention, there are some specific competencies that seafarers must have; minimizing the risk of fire and maintain a state of readiness to respond to emergency situations involving fire, and fight and extinguish fire (STCW, 1995). To increase these skills, the convention also determines required knowledge, understanding, and proficiency that crew’s member should have in order to properly handle the fire situation on board ships. Fire training should be involved with the shipboard firefighting organization, location of firefighting appliances and emergency escape routes, action to be taken on board ship, fire and smoke detection and automatic alarm system, which are considered substantial aspects for all firefighting situations. Further, firefighting equipment and its location on board ship requires special attention, therefore; fire training should put emphasis on this matter so that from fixed installation to firefighting procedures to use of breathing apparatus for firefighting and effective rescues should be elaborately involved the fire training (STCW, 1995).

In the some convention, minimum standard of competencies in advanced firefighting is also specified. Required competencies under this section are control firefighting operations on board ships, organize and train fire parties, inspected and service fire detection and fire extinguishing systems and equipment, and investigate and compile

reports on incidents involving fire. In detail, the section gives key aspects that trainers should focus on. Firefighting involving dangerous goods, fire precautions and hazards associated with the storage and handling of materials, management and control of injured person, procedures for coordination with shore-based fire fighters, strategies and tactics for control of fires in various parts of ships, assessment of cause of incidents involving fire are some the required knowledge and understanding that the fire training is aimed to provide to seafarers (STCW, 1995).

MTAB et al. (1994) recommended an experienced and effective training method that covers four steps, which are; preparation, presentation, confirmation, and demonstration. Preparation is imply that discuss the subject or equipment with the crews member in order to comprehend their knowledge and arise their curiosity about it. As a second step, presentation consists of the explanations, demonstrations, and even illustrations of the operation. The instructor should use several effective educational materials to explain each step of the operation. It is also important to emphasise the key points of the operation. At the confirmation part, the instructor should be ensure about the crews knows the required knowledge and can easily repeat the key points of the operation. Demonstration part is considered when the crew members demonstrate what have learned during the training. The crew members actively use tool, equipment and appliances at this step. The training should not end until the crew members correctly demonstrate the operation' requirements MTAB et al. (1994).

5. CASE STUDY

5.1 Problem Description

PSC survey results on shipboard highlights the significance of the fire related deficiencies. Same fire related deficiencies have encountered iteratively during the PSC inspections. Moreover, fire related deficiencies have contained relatively high portion of the total range. To illustarte, fire safety measures are indicated around 18% in Tokyo MOU PSC annual report (Tokyo MOU, 2012) while Paris MOU statistics about fire safety related deficiencies illustrate 15% (Paris MOU, 2012). Moreover, the statistical reports are other key document to follow the distribution of several deficiencies in operational level. For instance, Det Norske Veritas (DNV), IACS member prestigious classification society, reported that most commonly deficiency category deals with fire safety measures. It reaches 19% correspondingly (DNV, 2012). Another report published by American Bureau Shipping (ABS) illustrates that fire safety measures as the most common deficiency has the ratio of 16% compared to other categories (ABS, 2012). On the other hand, the report published by Nippon Kaiji Kyokai (ClassNK or NK) emphasis on fire safety measures related deficiencies whose percentage is around 24%. (ClassNK, 2012). In order to prevent the re-occurrence of the same fire related deficiencies, the study has aimed to reveale the root causes of these deficiencies, in the end; increase the ships fire safety.

5.2 Fire Related Deficiency Sample Database

The research has investigated great variety of maritime source, for example; DNV' annual deficiency report (DNV, 2012), ABS' Reducing the Port State Detention Factor report (ABS, 2012), Paris Mou' Taking PSC to the Next Level Annual report (Paris Mou, 2012), Tokyo Mou' Annual report on PSC (Tokyo Mou, 2012), and

ClassNK' annual report on PSC (NK, 2012). The investigation makes clear that some deficiencies encountered iteratively and these reports divided the fire related deficiencies into twenty main groups:

Table 5.1: Main deficiency groups.

No	Groups' name
1	Fire-dampers
2	Emergency fire pump
3	Fire prevention
4	Firefighting equipment and appliances
5	Fire detection
6	Fire doors within main vertical zone
7	Fixed fire extinguishing installation
8	Ready availability of firefighting equipment
9	Ventilation
10	Inert gas system
11	Division – main zones
12	Main vertical zone
13	Personal equipment
14	Means of control (opening, closure of skylights, pumps, etc. machinery spaces
15	Jacketed piping system for high pressure fuel lines
16	Fire control plan - all ships
17	International shore connection
18	Main fire pumps
19	Emergency Escape Breathing device (EEBD)
20	Other firefighting equipment

The inoperable fire dampers might lead to minor or major deficiencies, due to the inadequate familiarization, poor maintenance, adjustment mechanical parts, functional malfunctions, corrosion, sealing materials, flap positions, installations, etc. Another sub-group is poor condition of emergency fire pump caused by starting failures, self-priming issues, loss of pressure, leakages, remote control interruptions, electrical shortages, malfunctioned gauges, driven engine failures, fuel related matters. Fire prevention measures are also considered highly critical components of the fire safety on board ship. Oil leaks and improper storage of combustible materials contribute ships detention, as well. Firefighting equipment and appliances are also primarily factors that cause ships detention. Along with this sub-group deficiencies might be listed as follows: main fair line broken, leaking of the fire hose, firefighting equipment do not have mandatory certificate, incomplete firemen's outfits, etc.

Considering the fire detection equipment related deficiencies, PSC reports state number of cause, to illustrate, fire control and alarm systems disconnected for maintenance purposes, fire control and alarm systems covered by crew, and records of previous testing not available. Further, non-functional fire doors, keeping the fire doors in an open position, unauthorized cuts in fire zone boundaries, blocking the emergency escape routes are the example of the fire doors within main vertical zone related deficiencies that iteratively encountered during the PSC inspections. Regarding of the fixed fire extinguishing installation influence within the fire safety related deficiencies, company audits and vetting report founding's demonstrate some significant samples; empty or blocked fire boxes, expired fire extinguisher and breathing apparatus. Ready availability of firefighting equipment is one of the critical unit for emergency, therefore it cause detention if PSC inspectors encounter any violation associated with it. Moreover, ventilation related deficiencies are relatively high another elements that cause the deficiencies. For example, not operational, poor maintenance or corrosion related malfunctioning ventilation frequently encountered examples.

As listed above, there are also other essential components grouped under the fire related deficiencies. In order to avoid ships detention, responsible decision-makers and shipping company executives should consider all aspect of the issue. Inert gas system, division – main zones, main vertical zone, personal equipment, means of control, fire control plan – all ships, international shore connection, main fire pumps, emergency escape breathing device, other firefighting equipment's are the rest of the related main components.

5.3 Deficiency Causation (HFACS)

As mentioned earlier, HFACS classifies human related deficiencies in four categories. Under this sub-section, the study has utilized HFACS framework for the purpose of the classified fire related deficiencies. Considering the fire related deficiency sample database, HFACS unsafe acts level; preconditions for unsafe acts level; unsafe supervision level; organizational influences level are determined and demonstrates with the next tables respectively.

Table 5.2: HFACS first level causations.

Code	Causations
C1	Late responding to the sudden operational failure in critical components of fire system
C2	Misperception of fire related emergency situations complexity
C3	Responding to emergency fire related situations in panic
C4	Omitted step in fire safety related procedure
C5	Neglected items in fire frightening equipment routine inspection checklist
C6	Failed to prioritize actions to be taken during firefighting drills
C7	Misunderstanding of fire safety procedures
C8	Unorganized responding to fire related emergency situation
C9	Violated firefighting training and practice
C10	Failed to fulfilment of designated responsibilities in fire prevention
C11	Failed to properly use of firefighting equipment and appliances
C12	Failed to test and maintain standby arrangements of fire frightening alarm and equipment
C13	Use of fire firefighting's tool/equipment with a known defect
C14	Incorrect placement of portable tools, equipment or material in firefighting system
C15	Lack of safety culture about the use of personnel protective equipment
C16	Disable or remove safe guards, warning system or safety devices
C17	Inappropriate team integration and discipline in firefighting
C18	Lack of information due to poor emergency communication
C19	Distributed storage of materials and spares on board ship
C20	Missing and wrong labelling on firefighting equipment and appliances
C21	Violation of drugs and alcohol policies on board ship

Table 5.3: HFACS second level causations.

Code	Causations
C22	Loss of situational awareness in fire safety on board
C23	Misplaced motivation of crews on board
C24	Impaired physiological states of crews on board
C25	Lack of familiarization about fire safety
C26	Excessive self-confidence of crew members
C27	Physical fatigues of crews on board
C28	Time constraints on crew members' reaction in operational level
C29	Incompatible intelligence/aptitude of crews
C30	Insufficient physical capability in emergency response and actions
C31	Failed to communicate among ship and shore based organization in emergency situations
C32	Failed to coordinate the actions during the firefighting and fire related emergency situations
C33	Failed to conduct adequate operational planning and briefing
C34	Failed to use all available firefighting resources
C35	Poor coordination of fire frightening equipment and system
C36	Lack of warnings and signals about fire safety
C37	Increased concentration demands in fire related emergency situations
C38	Poor safety attitudes of crew due to basic health problems and illness
C39	Impairment of crew due to drug, alcohol or medication
C40	Other emotional overload of crews

Table 5.4: HFACS third level causations.

Code	Causations
C41	Failed to provide guidance's about fire prevention system
C42	Failed to provide dynamic operational plans against fire situation on board
C43	Failed to provide considerable level of supervision on board
C44	Failed to provide specific firefighting training along with different scenario
C45	Failed to ensure about qualification of crews embarkation on board ship
C46	Failed to continuously monitoring crew performance on board
C47	Failed to provide adequate audit time
C48	Ill-defined rules and responsibilities in fire safety plans
C49	Ignored crew resting hours
C50	Failed to update/revise documentation in fire safety plans
C51	Failed to identify fire related hazards on board ship
C52	Failed to initiate fire safety related corrective actions
C53	Failed to report unsafe fire prevention tendencies
C54	Failed to comply with fire safety rules and regulations
C55	Failed to collect data and evidences about fire safety measurement
C56	Lack of conditions assessment program for firefighting equipment
C57	Failure to correct repeating unsafe occurrences on board ship
C58	Lack of methodological tools and background to perform technical safety analysis
C59	Poor communication between supervisor and crew members on board ship

Table 5.5: HFACS fourth level causations.

Code	Causations
C60	The integration problem of company safety policy into operational level
C61	Poor design of ship fire system components
C62	Ergonomic design errors in fire safety installations
C63	Lack of systematic personnel selection and recruitment procedures
C64	Lack of managerial skill in shore-based personnel
C65	Financial resourcing/budget constraints to timely meet running/operational expenses
C66	Insufficient scope of crew training program
C67	Ineffective promotion system for crews
C68	Purchasing of firefighting equipment and appliances in low quality
C69	High level of documentation bureaucracy
C70	Lack of policy to monitor the required revisions in safety procedures
C71	Inefficient fire safety communication planning
C72	Fire control plans' inconsistencies
C73	Incorrect behavior enforced by shipping companies
C74	Excessive time pressure due to improper operational scheduling
C75	Lack of management tools to implement suitable preventive action planning on board
C76	Lack of effective system to determine adequate risk control options on board
C77	Management review input data incompleteness
C78	Lack of consistent improvement decisions and follow-up actions in management review output

5.4 Prioritization (FCM)

Fuzzy cognitive map has been constructed and investigated for the reason of that revealed the root causes of the fire related deficiencies. Initially, in order to specify the causal relationships between concepts, self-administered questionnaires are conducted. The questionnaires based on the domain experts' judgment, which they indicate for each ordered pair of distinct concepts (C_i, C_j) whether, *ceteris paribus*, a change in C_i has a significant impact on C_j . The experts use the linguistic scale, which is given in Figure 3.4, to express the degree of the causal relationship (weights) between two concepts. The number of causes considered in our FCM model is very high (i.e. 78 distinct causes), so that; it is a big challenge for experts to answer all pairwise questions (i.e. $78 \times (78-1) = 6006$) and the likelihood of the experts to introduce erroneous data increases (Asan and Soyer, 2009). Therefore, to make this questionnaire reliable and reduce the drawbacks, the adjacency matrix has been divided into 16 distinct regions with respect to the four levels in HFACS, as shown in Figure 5.1. Moreover, seven different groups of experts from the academia and industry are assigned with their area of expertise. These groups are: i) Maritime researchers (Group #1), ii) Maritime stakeholders (Group #2), iii) Port state control officers (Group #3), iv) Ship management executives (Group #4), v) Safety researchers (Group #5), vi) Industrial engineers (Group #6), and vii) Experienced seagoing officers/engineers (Group #7). By doing that, the study reduces the number of questions for each group of experts, while it improves the accuracy of judgments and the overall efficiency, as well.

	UA	PUA	US	OI
UA	Region 1 Group #7	Region 2 Group #5	Region 3 Group #3	Region 4 Group #1
PUA	Region 5 Group #5	Region 6 Group #5	Region 7 Group #4	Region 8 Group #1
US	Region 9 Group #3	Region 10 Group #4	Region 11 Group #4	Region 12 Group #6
OI	Region 13 Group #1	Region 14 Group #1	Region 15 Group #6	Region 16 Group #2

Figure 5.1: The partitioned adjacency matrix and the assigned expert groups.

Later, Max operator is utilized to generate the overall linguistic weights that obtained from a group of experts, consequently; the group of adjacency matrix. Next, the CoG defuzzification method is used to transforms the overall linguistic weight to crisp values. The calculations involved in the aggregation and defuzzification process regarding the impact of “Insufficient scope of crew training program (C66)” on “Failed to provide specific firefighting training along with different scenarios (C44)” in Region 15 are illustrated below. The linguistic weights obtained from two experts regarding this causal relationship are “moderately-strongly” and “strongly” (see Figure3.5). Thus, the CoG for the overall linguistic weight is calculated as follows:

$$z^* = \frac{\int_{0.6}^{0.8} \frac{(z - 0.6)}{0.2} z dz + \int_{0.8}^{0.9} \frac{(z - 1)}{-0.2} z dz + \int_{0.9}^1 \frac{z - 0.8}{0.2} z dz}{\int_{0.6}^{0.8} \frac{z - 0.6}{0.2} dz + \int_{0.8}^{0.9} \frac{(z - 1)}{-0.2} dz + \int_{0.9}^1 \frac{z - 0.8}{0.2} dz} = 0.834$$

Along with the stuyd, the experts are considered that each one of them has an equal weight of credibility. The adjacency matrices of both experts’ and the resulting matrix with crisp values are shown in Figures 5.2 to 5.4, respectively.

[illegible]

	C41	C42	C43	C44	C45	C46	C47	C48	C49	C50	C51	C52	C53	C54	C55	C56	C57	C58	C59
C60	0.8 1.0 1.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0
C61	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.2 0.4	0.0 0.0 0.0	0.0 0.0 0.0	0.6 0.8 1.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.8 1.0 1.0	0.0 0.0 0.0
C62	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.8 1.0 1.0	0.0 0.0 0.0	0.0 0.2 0.4	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0
C63	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.8 1.0 1.0	0.6 0.8 1.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.8 1.0 1.0
C64	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.2 0.4 0.6	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.2 0.4	0.0 0.0 0.2	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.6 0.8 1.0	0.0 0.2 0.4	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0
C65	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.2	0.2 0.4 0.6	0.6 0.8 1.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.2	0.6 0.8 1.0	0.0 0.0 0.0	0.0 0.0 0.0
C66	0.4 0.6 0.8	0.4 0.6 0.8	0.0 0.0 0.0	0.6 0.8 1.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.2 0.4 0.6	0.4 0.6 0.8	0.4 0.6 0.8	0.4 0.6 0.8	0.4 0.6 0.8	0.0 0.0 0.0	0.4 0.6 0.8	0.4 0.6 0.8	0.0 0.0 0.0
C67	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.8 1.0 1.0
C68	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.2	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0
C69	0.0 0.0 0.2	0.0 0.0 0.2	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.2	0.0 0.2 0.4	0.0 0.0 0.0	0.6 0.8 1.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.2	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.0 0.2	0.0 0.0 0.0	0.0 0.0 0.0
C70	0.0 0.0 0.0	0.0 0.0 0.2	0.2 0.4 0.6	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.2	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0
C71	0.4 0.6 0.8	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.8 1.0 1.0
C72	0.0 0.2 0.4	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0
C73	0.8 1.0 1.0	0.6 0.8 1.0	0.8 1.0 1.0	0.8 1.0 1.0	0.6 0.8 1.0	0.6 0.8 1.0	0.6 0.8 1.0	0.8 1.0 1.0	0.8 1.0 1.0	0.2 0.4 0.6	0.0 0.2 0.4	0.2 0.4 0.6	0.6 0.8 1.0	0.6 0.8 1.0	0.4 0.6 0.8	0.4 0.6 0.8	0.6 0.8 1.0	0.4 0.6 0.8	0.0 0.0 0.2
C74	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.2 0.4	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.2 0.4	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.2 0.4	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0
C75	0.8 1.0 1.0	0.0 0.0 0.0	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.0 0.2	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.2	0.0 0.0 0.0	0.0 0.0 0.0
C76	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0
C77	0.6 0.8 1.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.2	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.0	0.6 0.8 1.0	0.0 0.0 0.0	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.2 0.4 0.6	0.0 0.0 0.0	0.0 0.0 0.0
C78	0.0 0.0 0.0	0.4 0.6 0.8	0.0 0.0 0.0	0.0 0.0 0.0	0.6 0.8 1.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.2 0.4	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.0 0.0 0.0	0.6 0.8 1.0	0.0 0.0 0.0

	C41	C42	C43	C44	C45	C46	C47	C48	C49	C50	C51	C52	C53	C54	C55	C56	C57	C58	C59
C60	0.834	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C61	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.166	0.0	0.0	0.7	0.0	0.0	0.0	0.933	0.0
C62	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.834	0.0	0.4	0.7	0.0	0.0
C63	0.0	0.0	0.0	0.0	0.933	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.711
C64	0.0	0.0	0.0	0.3	0.6	0.0	0.0	0.3	0.289	0.5	0.0	0.0	0.0	0.7	0.3	0.0	0.0	0.6	0.0
C65	0.0	0.5	0.0	0.289	0.5	0.7	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.289	0.7	0.0	0.0
C66	0.5	0.5	0.0	0.834	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.5	0.6	0.7	0.422	0.0	0.6	0.6	0.0
C67	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.834
C68	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.166	0.0	0.0	0.6	0.0
C69	0.289	0.289	0.289	0.0	0.0	0.0	0.422	0.3	0.0	0.834	0.0	0.0	0.289	0.0	0.4	0.0	0.166	0.0	0.0
C70	0.0	0.166	0.4	0.5	0.0	0.0	0.4	0.166	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0
C71	0.6	0.5	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.933
C72	0.3	0.7	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0
C73	0.933	0.7	0.933	0.834	0.7	0.7	0.8	0.933	0.933	0.4	0.3	0.5	0.8	0.8	0.5	0.6	0.7	0.6	0.166
C74	0.0	0.5	0.0	0.0	0.0	0.166	0.5	0.0	0.3	0.0	0.0	0.0	0.3	0.0	0.4	0.0	0.5	0.0	0.0
C75	0.834	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.289	0.0	0.0	0.289	0.0	0.0
C76	0.0	0.7	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C77	0.8	0.0	0.0	0.0	0.0	0.166	0.0	0.5	0.0	0.8	0.0	0.0	0.6	0.0	0.0	0.0	0.4	0.0	0.0
C78	0.0	0.7	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.166	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0

Figure 5.4: The aggregated adjacency matrix for Region 15.

In the following step, the direct relationships represented in the aggregated adjacency matrix are examined. Using Eqs. (3.3) and (3.4), the outdegree and indegree, in other words the cumulative strengths of connections entering and exiting the concepts are calculated. These values, which serve to identify the role of each concept in the system, are depicted in Figure 5.5. For example, it can be suggested that the concepts C66, C73 and C74 are highly influential causes, while C8, C10 and C11 are highly dependent on the rest of the system. Since we are basically interested in identifying the potential root causes, concepts deserving this characteristic should fulfil the rules provided in Eq. (3.5a) and (3.5b). In this particular case, the average outdegree taken over the entire concept set is found to be approximately 13.6. Accordingly, for concept i , if $od(i) \geq 13.6$ and $IPI_i \geq 2$ then the concept will be considered as a potential root cause. These rules are depicted in Figure 5.5, where the dashed line represents $IPI = 2$ and the solid line represents the average outdegree. For example, C66 is a potential root cause, since $od(66) = 28.1$, $id(66) = 4.8$ and $IPI_{66} = 28.1/4.8 = 5.85$. Table 5.6 summarizes the results of the direct relationships analysis. Finally, according to the direct relationship analysis the potential root causes identified are C21, C26, C48, C49, C58, C62, C64, C66, C67, C71, C72, C73, C74, and C75.

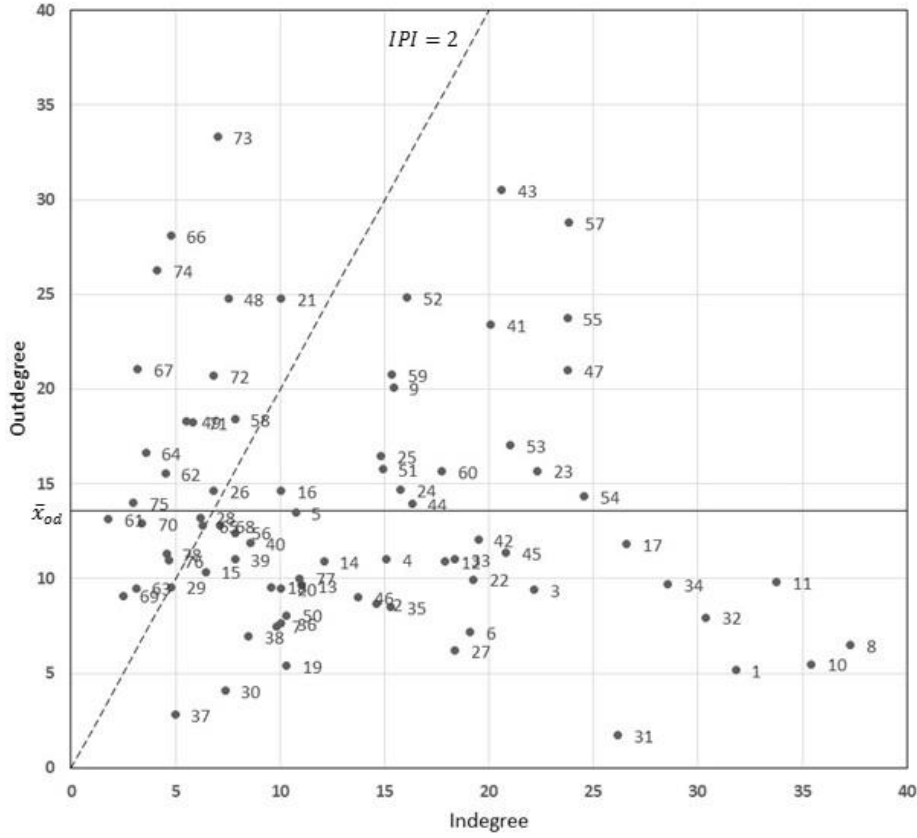


Figure 5.5: Influence-dependence chart for direct relationships (dashed line represents $IPI=2$, solid line represents $\bar{x}_{od} = 13.6$).

Table 5.6: Results of the analysis of direct relationships.

Cause	$od(i)$	$id(i)$	IPI_i	$od(i) \geq 13.6$	$IPI_i \geq 2$	Potential Root Cause
C1	5.1	31.9	0.16	No	No	No
C2	8.7	14.7	0.59	No	No	No
C3	9.4	22.2	0.42	No	No	No
C4	11.0	15.1	0.73	No	No	No
C5	13.5	10.8	1.25	No	No	No
C6	7.1	19.1	0.37	No	No	No
C7	7.5	9.9	0.76	No	No	No
C8	6.5	37.3	0.17	No	No	No
C9	20.1	15.5	1.30	Yes	No	No
C10	5.5	35.5	0.15	No	No	No
C11	9.8	33.8	0.29	No	No	No
C12	10.9	17.9	0.61	No	No	No
C13	9.6	11.1	0.87	No	No	No
C14	10.9	12.1	0.90	No	No	No
C15	10.3	6.5	1.60	No	No	No
C16	14.6	10.1	1.45	Yes	No	No
C17	11.8	26.6	0.44	No	No	No
C18	9.5	9.6	0.99	No	No	No

Table 5.6 (continued)

Cause	$od(i)$	$id(i)$	IPI_i	$od(i) \geq 13.6$	$IPI_i \geq 2$	Potential Root Cause
C19	5.4	10.3	0.52	No	No	No
C20	9.5	10.1	0.94	No	No	No
C21	24.7	10.1	2.46	Yes	Yes	Yes
C22	9.9	19.3	0.52	No	No	No
C23	15.7	22.3	0.70	Yes	No	No
C24	14.7	15.8	0.93	Yes	No	No
C25	16.5	14.9	1.11	Yes	No	No
C26	14.6	6.9	2.13	Yes	Yes	Yes
C27	6.2	18.4	0.34	No	No	No
C28	13.2	6.2	2.13	No	Yes	No
C29	9.5	4.8	1.99	No	No	No
C30	4.1	7.4	0.55	No	No	No
C31	1.7	26.2	0.07	No	No	No
C32	7.9	30.4	0.26	No	No	No
C33	11.0	18.4	0.60	No	No	No
C34	9.7	28.6	0.34	No	No	No
C35	8.5	15.3	0.55	No	No	No
C36	7.6	10.1	0.75	No	No	No
C37	2.8	5.0	0.56	No	No	No
C38	6.9	8.5	0.81	No	No	No
C39	11.0	7.9	1.40	No	No	No
C40	11.9	8.6	1.38	No	No	No
C41	23.4	20.1	1.16	Yes	No	No
C42	12.0	19.5	0.62	No	No	No
C43	30.5	20.6	1.48	Yes	No	No
C44	13.9	16.3	0.85	Yes	No	No
C45	11.3	20.8	0.54	No	No	No
C46	9.0	13.8	0.65	No	No	No
C47	21.0	23.8	0.88	Yes	No	No
C48	24.7	7.6	3.27	Yes	Yes	Yes
C49	18.3	5.5	3.31	Yes	Yes	Yes
C50	8.0	10.3	0.78	No	No	No
C51	15.8	14.9	1.06	Yes	No	No
C52	24.8	16.1	1.54	Yes	No	No
C53	17.0	21.1	0.81	Yes	No	No
C54	14.3	24.6	0.58	Yes	No	No
C55	23.7	23.8	1.00	Yes	No	No
C56	12.4	7.9	1.57	No	No	No
C57	28.8	23.8	1.21	Yes	No	No
C58	18.4	7.9	2.34	Yes	Yes	Yes
C59	20.7	15.4	1.35	Yes	No	No
C60	15.6	17.8	0.88	Yes	No	No
C61	13.1	1.8	7.29	No	Yes	No
C62	15.5	4.5	3.43	Yes	Yes	Yes
C63	9.5	3.1	3.02	No	Yes	No

Table 5.6 (continued)

Cause	$od(i)$	$id(i)$	IPI_i	$od(i) \geq 13.6$	$IPI_i \geq 2$	Potential Root Cause
C64	16.6	3.6	4.61	Yes	Yes	Yes
C65	12.8	6.3	2.02	No	Yes	No
C66	28.1	4.8	5.85	Yes	Yes	Yes
C67	21.0	3.2	6.57	Yes	Yes	Yes
C68	12.8	7.1	1.79	No	No	No
C69	9.1	2.6	3.55	No	Yes	No
C70	12.9	3.4	3.75	No	Yes	No
C71	18.2	5.8	3.12	Yes	Yes	Yes
C72	20.7	6.9	3.01	Yes	Yes	Yes
C73	33.3	7.0	4.73	Yes	Yes	Yes
C74	26.3	4.1	6.34	Yes	Yes	Yes
C75	14.0	3.0	4.65	Yes	Yes	Yes
C76	10.9	4.7	2.33	No	Yes	No
C77	10.0	11.0	0.91	No	No	No
C78	11.3	4.6	2.45	No	Yes	No

A similar classification is performed in the analysis of indirect relationships. Here, the diffusion of causal impacts through reaction paths and loops are considered to explore hidden root causes. To do this, the adjacency matrix is raised to successive powers. In this study, the adjacency matrix is raised to the sixth power ($q = 6$) where the concepts' order proves to be stable. The outdegree and indegree values in each resulting matrix ($q = 1, \dots, 6$) are then normalized to enable a comparison among the results of successive powers. For example, the normalized values of C66 for $q = 2$ are calculated using Eq. (3.7) and (3.8) as follows:

$$Nod(66)^2 = \frac{\max_{i=1 \dots 78} \{od(i)\} \cdot od(66)^2}{\max_{i=1 \dots 78} \{od(i)^2\}} = \frac{33.3 \cdot 342.3}{513.2} = 22.2$$

$$Nid(66)^2 = \frac{\max_{i=1 \dots 78} \{id(i)\} \cdot id(66)^2}{\max_{i=1 \dots 78} \{id(i)^2\}} = \frac{37.3 \cdot 56.1}{496.4} = 4.2$$

Consequently, the total outdegree and indegree values of C66, which indicate the reachability of this concept, is calculated as follows

$$\begin{aligned}
Rod(66) &= \frac{(\sum_{q=1}^6 Nod(66)^q)}{6} \\
&= (28.1 + 22.2 + 22.7 + 22.4 + 22.4 + 22.4)/6 \\
&= 23.4
\end{aligned}$$

$$\begin{aligned}
Rid(66) &= \frac{(\sum_{q=1}^6 Nid(66)^q)}{6} \\
&= (4.8 + 4.2 + 3.8 + 3.7 + 3.7 + 3.7)/6 = 4.0
\end{aligned}$$

The total outdegree and indegree values of the concepts are depicted in Figure 5.6. To identify the potential root causes, the same rules suggested in the direct relationships analysis are employed here. In other words, those concepts fulfilling the rules $Rod(i) \geq 11.9$ and $IPI_i \geq 2$ are considered as potential root causes (see Figure 5.6). Table 5.7 summarizes the results of the indirect relationships analysis, where C48, C58, C64, C65, C66, C67, C71, C72, C73, and C74 are labeled as potential root causes. Notice that C65 is one hidden root cause which is supposed to be unimportant with respect to the direct relationships. Therefore, comparing the results of the two analyses can help to confirm the importance of certain concepts as potential root causes and can reveal hidden root causes which are previously thought to be unimportant but play a critical role because of indirect impacts.

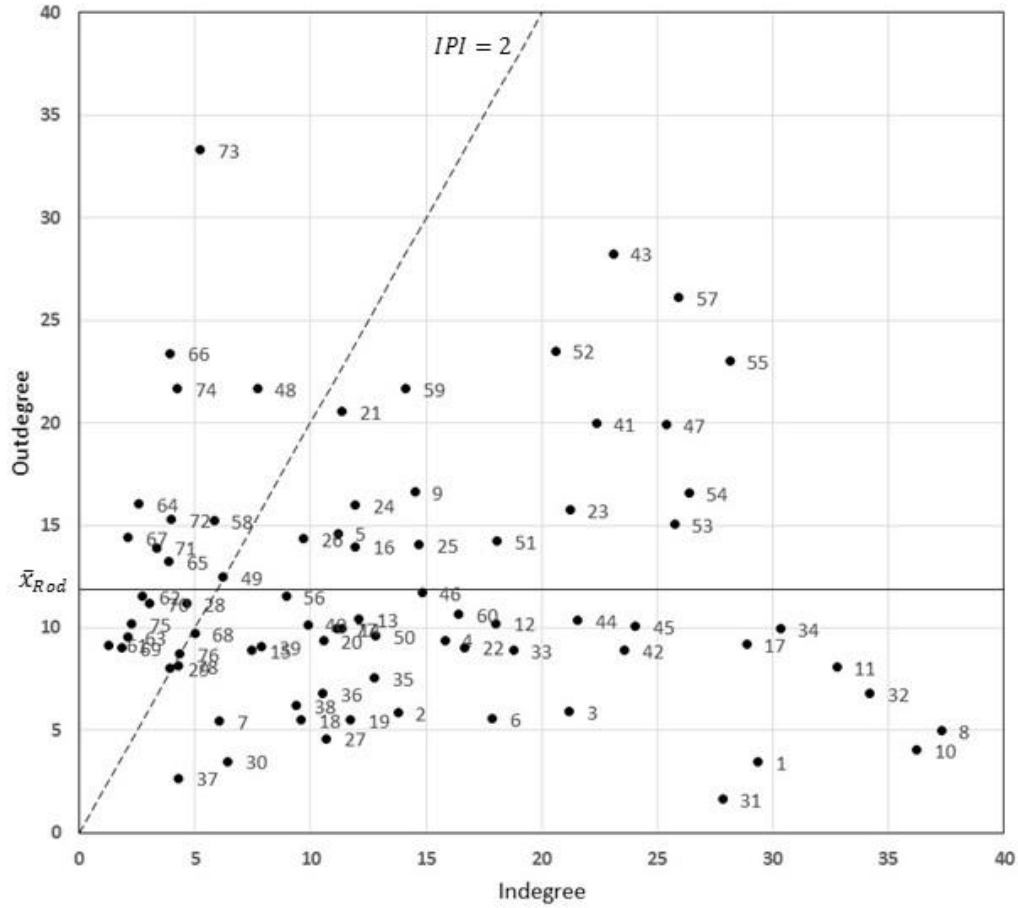


Figure 5.6: Influence-dependence chart for indirect relationships (dashed line represents $IPI=2$, solid line represents $\bar{x}_{Rod} = 11.9$).

Table 5.7: Results of the analysis of indirect relationships.

Cause	$Rod(i)$	$Rid(i)$	IPI_i	$Rod(i) \geq 11.9$	$IPI_i \geq 2$	Potential Root Cause
C1	3.4	29.4	0.12	No	No	No
C2	5.8	13.8	0.42	No	No	No
C3	5.9	21.2	0.28	No	No	No
C4	9.4	15.9	0.59	No	No	No
C5	14.6	11.2	1.30	Yes	No	No
C6	5.5	17.9	0.31	No	No	No
C7	5.4	6.1	0.89	No	No	No
C8	5.0	37.3	0.13	No	No	No
C9	16.6	14.5	1.14	Yes	No	No
C10	4.0	36.3	0.11	No	No	No
C11	8.1	32.8	0.25	No	No	No
C12	10.2	18.1	0.56	No	No	No
C13	10.4	12.1	0.86	No	No	No
C14	9.9	11.4	0.87	No	No	No
C15	8.9	7.5	1.19	No	No	No

Table 5.7 (continued)

Cause	$Rod(i)$	$Rid(i)$	IPI_i	$Rod(i) \geq 11.9$	$IPI_i \geq 2$	Potential Root Cause
C16	13.9	12.0	1.17	Yes	No	No
C17	9.2	28.9	0.32	No	No	No
C18	5.5	9.6	0.57	No	No	No
C19	5.5	11.8	0.47	No	No	No
C20	9.3	10.6	0.88	No	No	No
C21	20.5	11.4	1.80	Yes	No	No
C22	9.0	16.7	0.54	No	No	No
C23	15.7	21.2	0.74	Yes	No	No
C24	15.9	12.0	1.33	Yes	No	No
C25	14.0	14.7	0.96	Yes	No	No
C26	14.3	9.7	1.47	Yes	No	No
C27	4.6	10.7	0.43	No	No	No
C28	11.2	4.7	2.40	No	Yes	No
C29	8.0	4.0	2.02	No	Yes	No
C30	3.5	6.4	0.54	No	No	No
C31	1.6	27.8	0.06	No	No	No
C32	6.8	34.2	0.20	No	No	No
C33	8.9	18.8	0.47	No	No	No
C34	9.9	30.3	0.33	No	No	No
C35	7.5	12.8	0.59	No	No	No
C36	6.8	10.5	0.64	No	No	No
C37	2.6	4.3	0.61	No	No	No
C38	6.2	9.4	0.66	No	No	No
C39	9.0	7.9	1.14	No	No	No
C40	10.1	9.9	1.02	No	No	No
C41	19.9	22.4	0.89	Yes	No	No
C42	8.9	23.6	0.38	No	No	No
C43	28.2	23.1	1.22	Yes	No	No
C44	10.4	21.6	0.48	No	No	No
C45	10.0	24.1	0.42	No	No	No
C46	11.7	14.9	0.79	No	No	No
C47	19.9	25.4	0.78	Yes	No	No
C48	21.6	7.7	2.80	Yes	Yes	Yes
C49	12.5	6.2	2.00	Yes	No	No
C50	9.6	12.8	0.75	No	No	No
C51	14.2	18.1	0.78	Yes	No	No
C52	23.5	20.6	1.14	Yes	No	No
C53	15.0	25.8	0.58	Yes	No	No
C54	16.5	26.4	0.63	Yes	No	No
C55	23.0	28.2	0.82	Yes	No	No
C56	11.5	9.0	1.28	No	No	No
C57	26.1	25.9	1.01	Yes	No	No
C58	15.2	5.9	2.60	Yes	Yes	Yes
C59	21.7	14.2	1.53	Yes	No	No
C60	10.6	16.4	0.65	No	No	No
C61	9.1	1.3	7.05	No	Yes	No

Table 5.7 (continued)

Cause	$Rod(i)$	$Rid(i)$	IPI_i	$Rod(i) \geq 11.9$	$IPI_i \geq 2$	Potential Root Cause
C62	11.5	2.7	4.22	No	Yes	No
C63	9.5	2.1	4.51	No	Yes	No
C64	16.0	2.6	6.15	Yes	Yes	Yes
C65	13.2	3.9	3.40	Yes	Yes	Yes
C66	23.4	4.0	5.89	Yes	Yes	Yes
C67	14.4	2.1	6.70	Yes	Yes	Yes
C68	9.7	5.0	1.93	No	No	No
C69	9.0	1.9	4.76	No	Yes	No
C70	11.2	3.1	3.65	No	Yes	No
C71	13.9	3.4	4.10	Yes	Yes	Yes
C72	15.3	4.0	3.80	Yes	Yes	Yes
C73	33.3	5.2	6.35	Yes	Yes	Yes
C74	21.6	4.2	5.09	Yes	Yes	Yes
C75	10.2	2.3	4.43	No	Yes	No
C76	8.7	4.4	1.99	No	No	No
C77	9.9	11.2	0.89	No	No	No
C78	8.1	4.3	1.87	No	No	No

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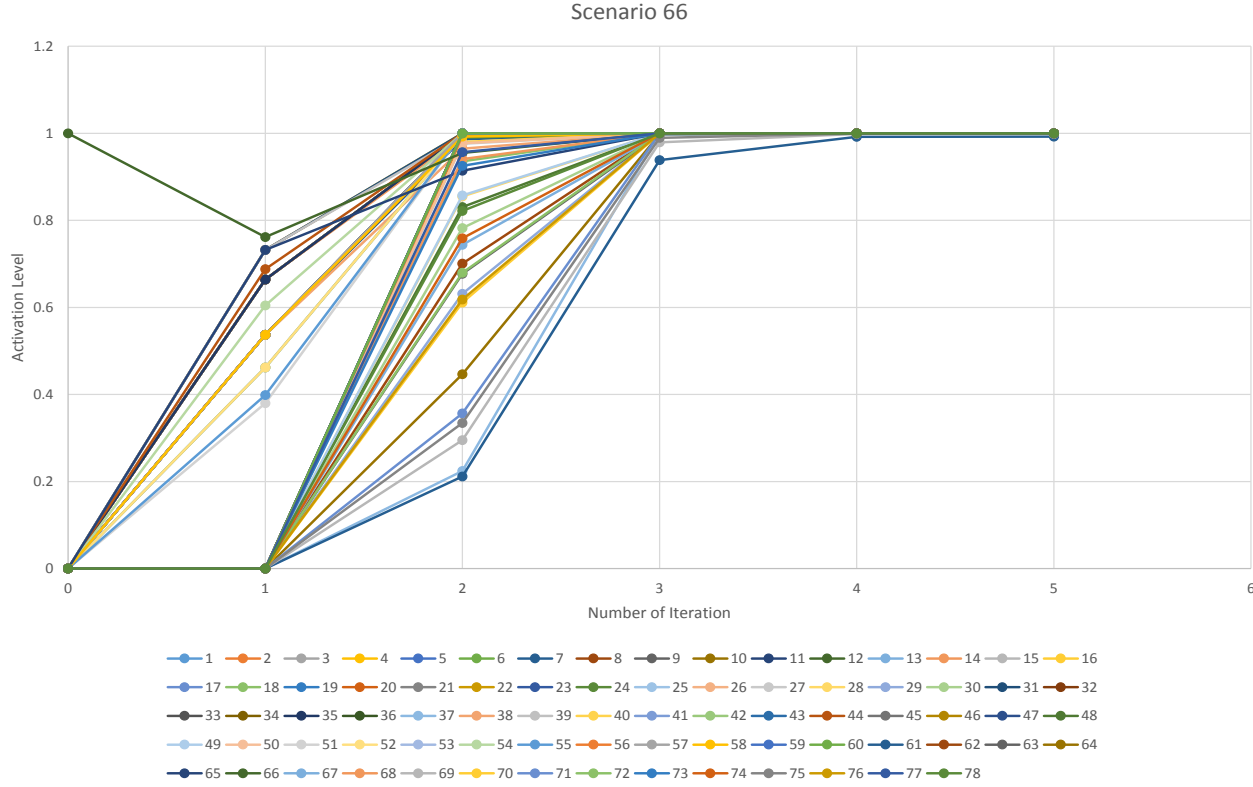


Figure 5.7: Results of the FCM simulation process for Scenario 66.

The results of the 78 different scenarios suggest that the system converges toward a steady state in maximum four iterations, and in all scenarios only 25 causes reach an activation level of exact 1 (the rest ends up between 0.98-0.99). A critical indicator in these simulations is the number of concepts influenced in the early iterations by a particular concept. Those concepts influencing a higher number of concepts in the early iterations are supposed to be more likely a root cause. Consequently, the decision on the final list of root causes is made by synthesizing the results of Step 3, 4 and 5. The results are provided in Table 5.8. The priorities are determined based on the averages of rank orders of the scenarios with respect to iterations one and two. For example, the most influential root cause is “Incorrect behavior enforced by shipping companies” which activates 41 concepts in the first iteration and 77 concepts in the second. Finally, the root causes listed according to their priorities are C73, C74, C66, C48, C58, C64, C72, C21, C65, C62, C67, C71, C26, C75 and C49.

Table 5.8: Priorities of potential root causes.

Scenario	Activated Cause	# of Activated concepts (>0.5)			Rank Order w.r.t. I1	Rank Order w.r.t. I2	Priority
		iteration 1 (I1)	iteration 2 (I2)	iteration 3 (I3)			
21	C21	29	65	77	4,5	10,5	8
26	C26	16	65	77	14	10,5	13
48	C48	29	72	77	4,5	6	4
49	C49	19	52	77	11	15	15
58	C58	22	74	77	8	5	5
62	C62	20	66	77	10	9	10
64	C64	17	77	77	12,5	1,5	6
65	C65	14	76	77	15	3,5	9
66	C66	35	71	77	2,5	7	3
67	C67	26	62	77	7	13,5	11
71	C71	21	62	77	9	13,5	12
72	C72	27	70	77	6	8	7
73	C73	41	77	77	1	1,5	1
74	C74	35	76	77	2,5	3,5	2
75	C75	17	63	77	12,5	12	14

5.5 Integration (Preventive action planning)

The model clearly reveals the common root causes of fire related deficiencies based on their priorities stated in the Table 5.9:

Table 5.9: The common root causes.

Priority	Root causes
1	Incorrect behaviour enforced by shipping companies (C73)
2	Excessive time pressure due to improper operational scheduling (C74)
3	Insufficient scope of crew training program (C66)
4	Ill-defined rules and responsibilities in fire safety plans (C48)
5	Lack of methodological tools and background to perform technical safety analysis (C58)
6	Lack of managerial skill in shore-based personnel (C64)
7	Fire control plans' inconsistencies (C72)
8	Violation of drugs and alcohol policies on board ship (C21)
9	Financial resourcing/budget constraints to timely meet running/operational expenses (C65)
10	Ergonomic design errors in fire safety installations (C62)
11	Ineffective promotion system for crews (C67)
12	Inefficient fire safety communication planning (C71)
13	Excessive self-confidence of crew members (C26)
14	Lack of management tools to implement suitable preventive action planning on board (C75)
15	Ignored crew resting hours (C49)

Now, it is an onerous task to successfully eliminate the featured factors via suggesting effective preventive actions systematically. In this stage, so-called as integration, the research explores the preventive actions rather than relatively simple corrective actions which are mainly preferred in majority of ship fleets. Hence, it requires a genius approach to produce comprehensive solutions especially along with the latent error sources. For instance, in unsafe act level, violation of drugs and alcohol policies on board ship (C21) is found as the most contributing factor since it directly influences the cognitive, physical and mental performance during operations. The nature of fire events on-board ships extremely require team integrity which might be influenced by excessive self-confidence of crew members (C26) respectively. On the other hand, the combination of inefficient emergency communication (C71), ill-defined rules and responsibilities in fire safety plans (C48) and relevant inconsistencies (C72) will reduce the response level to the complex situations. In addition to the key operational challenges that many organizations recently facing such as crew resting hours (C49), excessive time constraints (C74), running costs (C65), the design phase should also consider additional ergonomic aspects (C62) to support safety level at sea. On the other hand, a ship-owner tendency in terms of affecting organizational behaviour of company (C73) is one of the dominating factors whose effects are widely seen in each level. As another core aspect, operating crew qualifications, highly depend on consistent promotion (C66) and effective training (C67), should be enough to overcome complex hazardous occurrences. Finally, managerial capabilities (C64) supporting with advance analysis and execution tools (C58, C75) have been playing an onerous role to ensure continuous improvement of fire-fighting capability on-board ships.

It is clearly seemed that the determined root causes directly fall within the scope of prevention, mitigation, preparedness, response and recovery strategies against fire related emergency situations. Establishing a continuous proactive system is the final step of this research. Considering the determined root causes, ship operating environment and recent marine technologies, it is a great necessity to produce effective prevention actions comprehensively. It means that a preventive action proposal should be in generic form, originated from certain root causes, and applicable to various types of fleet in order to recurrence of focused operational

facts. Table 5.10 provides the suggested mechanisms as preventive action proposals in accordance with their priorities.

Table 5.10: Preventive action proposals.

Suggested Mechanisms	Eliminated root causes						
	Application priorities						
	1	2	3	4	5	6	7
Safe Ship System Mechanism (SSSM)	C72	C62	C71				
Safe Ship Operation Mechanism (SSOM)	C74	C66	C48	C65	C67	C26	C49
Safe Ship Execution Mechanism (SSEM)	C73	C58	C64	C21	C75		

The suggested mechanism includes Safe Ship System Mechanism (SSSM), Safe Ship Operation Mechanism (SSOM) and Safe Ship Execution Mechanism (SSEM). The priorities of root causes derived from qualitative simulation application are used to scheduling of preventive action proposals produced within the suggested mechanism. Besides ensuring a systematic approach, the mechanisms also classify the root causes and corresponding solutions in design, operation and management perspectives.

For instance, the function of SSSM is to ensure system operability, maintainability, equipment reliability via testing arrangements, design and installation monitoring. Especially, the ergonomics of user interfaces are the main concern of SSSM. In practice, the SSSM produces invaluable feedbacks to design and construction phases of fire control and safety system at new buildings as well as the reconstruction, conversion, repair and maintenance processes of existing ships in fleet. Hence, SSSM provides continuous response against defective elements in system level, leading to firefighting vulnerabilities, will be provided. To achieve that, the SSSM requires establishing and integrating the following subsystems: i) safe design and installation feedback system, ii) operability monitoring system, iii) equipment reliability assessment system.

On the other hand, SSOM mainly targets to improve safety awareness in shipboard operations. For example, an advance scheduling and responsibility allocation system should be established to control the time constraints on operational processes.

Identification of suitable training items is another critical point of interest that can be supported problem-based training including regulatory amendments rather than traditional safety trainings. The experienced operational safety cases should be analysed and shared with critical lessons to be learned. The motivating factors (i.e. resting hours' compliance, fair promotion process, etc.) should be considered and systematically actualized in order to enable the high number of good practices on-board. Remedying the mentioned issues, the SSOM should be supported with following sub-systems: i) safe operation verification system, ii) crew improvement program, iii) safety regulation compliance system.

In organizational level, the SSEM deals with governing the overall process of fire safety improvement at sea. The mechanism might require organizational redesign to challenge with the incorrect organizational behaviour, ordinary policies and management practices. It is the most significant issue to be revised. It might inquisitively effect the management review decisions, utilization of methodological tools, even existing managerial skills, and specific policies. In this cycle, the mentioned attempts will improve the proactive fleet management capability. Since the majority of deficiencies have been occurred with the combination of root causes, the strength safety barriers in organizational level have potential to eliminate the shaping or interactions of various root causes. In organization level, the SSEM necessitates to adopt following sub-systems: i) safety performance measurement system ii) safety management database, iii) operational problem analysis and solution system.

6. CONCLUSION

Maritime transportation has a privileged position among the other transportation modes, since; maritime transportation provides cost effective, safe, secure, and environmental friendly transportation. Because of the technological developments, ships are getting bigger, so unit transportation cost becomes more competitive. Further, considering the carbon and sulfur dioxide emissions, maritime transportation is relatively environmental friendly transportation mode. More importantly, maritime transportation is one of the most safe transportation modes. The economic crises, energy shortages, and environmental concerns make these advantages invaluable for the modern human life; therefore it is highly critical manner to improve maritime transportation advantages.

Despite the all mentioned advantages, maritime transportation can cause catastrophic accidents that damage the cargoes, ships, environment, and even human life. In order to improve maritime safety, prevent marine accidents and pollutions from ships, International Maritime Organization (IMO) has implemented hundreds of codes, regulations, and guidelines. However, essential amendments have been implemented after the catastrophic accidents, so its regulations derived from the learning from accidents. The last amendments on the ISM Code in Manila in 2010, on the other hand, can be considered proactive, which implies the take the required precautions before the accidents happened. According to this amendment, maritime organizations are expected to re-design their safety requirements to comply with the international regulations.

Among the other maritime accidents, fire accidents are one of the most frequently encountered and damaging accidents type, which is generally result from ships total loss, large amount of financial loss, and loss of human life. In addition, after an accident, maritime organization might suffer from the loss of goodwill, so it put at danger the organization outlook. Therefore, it is significantly important to prevent the fire accidents on board ships. At these insights, this study have been dedicated to

develop a proactive modeling approach, named HFACS-FCM model, which improves a ship/fleet fire safety.

The study has investigated PSC inspection reports, company audits reports, near-miss reports, accident reports, vetting survey results, other inspection reports to reveal the most encountered fire related deficiencies. With respect to the inspected reports, fire related deficiencies are divided into twenty main groups. Next, the Human Factor Analysis and Classification System (HFASC) are utilized to classify human related deficiencies. HFACS have been utilized in this study because of its proved and reliable systematic framework. More importantly, besides active reasons, HFACS enables the study to analyze the latent factors in the systems. After that, the study takes advantage of the Fuzzy Cognitive Map (FCM) in order to prioritize the deficiencies. FCM is advanced, reliable, and consistent model, which can be used where reliable data is missing or not available. Maritime industry has several disadvantages about the reaching the reliable data to investigate or analyze the industry. By using the FCM, the study has overcome these disadvantages. Further, FCM is relatively simple and flexible framework compare to other modes (e.g. system dynamic). Supported with qualitative simulations, HFACS-FCM model help predicting and eliminating the root causes behind the frequently repeating fire related deficiencies on board ships.

The study results underline the fact that unsafe acts level has relatively slight effect over the ship fire system, considering the only one root cause belongs to HFACS first level. However, drugs and alcohol (C21) directly influence the crews' cognitive, physical and mental performance, therefore it consequences might be devastating; regarding the firefighting is required excessive physical and mental effort. Firefighting also required effective teamwork, so that team integrity is extremely critical manner, as study results indicate; excessive self-confidence of crew members (C26) is one of the root causes that belongs to pre-condition for unsafe acts level. Moreover, the latent factors that are belongs to unsafe supervision level strongly affects the system safety. For instance; Ill-defined rules and responsibilities in fire safety plans (C48), ignored crew resting hours (C49) significantly affects the crews respond the unexpected fire events. Lack of methodological tools and background to perform technical safety analysis (C58) root cause prevent the developing proper firefighting plans. Above all, organizational influences are the most critical aspect that system safety depends on. The study results clearly emphasize that budget

constraints and economic situation of company highly important for the ship safety, to illustrate; excessive time pressure due to improper operational scheduling (C74), financial resourcing/budget constraints to timely meet running/operational expenses (C65) is one of the root causes. Managerial competencies also one of most core aspect of the ship safety; incorrect behavior enforced by shipping companies (C73), lack of managerial skill in shore-based personnel (C64), inefficient fire safety communication planning (C71), insufficient scope of crew training program (C66), ineffective promotion system for crews (C67). Further, ergonomic design errors in fire safety installations (C62) and lack of management tools to implement suitable preventive action planning on board (C75) is also playing a crucial role to ensure continuous improvement of fire-fighting. Taking consideration the HFACS-FCM model results, the study have suggested three mechanisms which are Safe Ship System Mechanism (SSSM), Safe Ship Operation Mechanism (SSOM) and Safe Ship Execution Mechanism (SSEM) to systematically eliminate the fire related deficiencies on board ships. SSSM is related with the system operability and equipment reliability, while SSOM aims to improve safety awareness on ship operations. On the other hand, SSEM targets to the overall execution process of fire safety on board ships.

The study result clearly indicates that HFACS-FCM model is reliable and applicable for ships to improve the fire safety. Further, thanks to its flexible framework, the model can be used for a single ship, fleet or even for other risky industries. Take advantage of the HFACS and FCM, the model is considered advanced hybrid model. Despite the complex and dynamic involvement between the human element and other ships' sub-systems, the model is relatively simple and effective. Human element has been considered one of the main causes of the marine accidents; so understanding of its role in the maritime transportation is invaluable. Therefore, the study has focused on the human element to develop effective and sufficient proactive model. Used to advance methods, the study capable of the reveal not only active reasons but also latent factors that significantly effects the system reliability in most cases. In order to the increase the model consistency, qualitative simulations have been utilized in the investigation. Eliminating the root causes systematically and effectively, three comprehensive mechanisms are suggested to improve ships fire safety.

Consequently, the study has accomplished to eliminate the root causes and strength the response and preparedness level, which are considered two key points to improve a ship safety. Therefore, the study significantly contributes to not only maritime safety literature but also maritime industry. Moreover, the study also encourages the maritime researchers to produce proactive fire safety systems that based on the advanced models.

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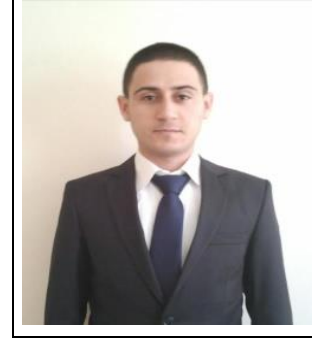
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