ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

A RULE-BASED HUMAN RELIABILITY ASSESSMENT TO ENHANCE SHIP AUXILIARY MACHINERY MAINTENANCE OPERATIONS

Ph.D. THESIS

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AUGUST 2020

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

GEMİ YARDIMCI MAKİNELERİ BAKIM ONARIM OPERASYONLARININ İYİLEŞTİRİLMESİ İÇİN KURAL TABANLI İNSAN GÜVENİLİRLİĞİ ÖLÇÜMÜ

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Date of Submission : 20 July 2020
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In dedication to my only brother,

FOREWORD

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TABLE OF CONTENTS

Page

ABBREVIATIONS

ACIH	: Analysis of Consequences of Human Unreliability
AHP	: Analytic Hierarchy Process
APOA	: Assessed Proportion of Affect
AR	: Augmented Reality
ATHEANA	: A Technique for Human Error Analysis
CARA	: Controller Action Reliability Assessment
CBM	: Conditon Based Maintenance
CPS	: Cyber-Physical Systems
CR	: Consistency Rate
CM	: Corrective Maintenance
CREAM	: Cognitive Reliability and Error Analysis Method
DEMATEL	: Decision Making Trial and Evaluation Laboratory
EPC	: Error Producing Condition
GEP	: Generic Error Probability
GTT	: Generic Task Type
HEART	: Human Error Assessment and Reduction Technique
HFACS	: Human Factor Analysis and Classification System
H-RAMS	: Human Reliability Analysis and Monitoring System Proposal in Shipboard Operations
HFACS-MMO	: Human Factor Analysis and Classification System for Marine Maintenance and Operations
HEP	: Human Error Probability
HFO	: Heavy Fuel-Oil
HRA	: Human Reliability Analysis
ILO	: International Labor Organization
IMO	: International Maritime Organization
IoP	: Internet of People
IoS	: Internet of Services
IoT	: Internet of Things
ISM	: International Safety Management Code
MARPOL	: International Convention for the Prevention of Pollution from Ships
MMO-EPC	: Marine Maintenance and Operations Specific Error Producing Conditions
SOHRA	: Shipboard Operations Human Reliability Analysis
MCDM	: Multi-criteria Decision Making
MMOHRA	: Marine Maintenance and Operations Human Reliability Analysis
NARA	: Nuclear Action Reliability Assessment
PDM	: Predictive Maintenance
PM	: Preventive Maintenance
PMS	: Planned Maintenance Schedule
PRELUDE	: Performance Shaping Factor Based Human Reliability Assessment Using Valuation-Based

PSC	**:** Port State Control
PSF	**:** Performance Shaping Factor
RARA	**:** Railway action reliability assessment
RCM	**:** Reliability Centered Maintenance
RFID	**:** Radio Frequency Identification
RI	**:** Random Index
RTF	**:** Run to Failure
SCADA	**:** Supervisory Control & Data Acquisition Systems
SLIM	**:** Success Likelihood Index Methodology
SOLAS	**:** International Convention for the Safety of Life at Sea
STCW	**:** Standards of Training, Certification and Watchkeeping for Seafarers
SPAR-H	**:** Simplified Plant Analysis Risk Human Reliability Assessment
THERP	**:** Technique for Human Error Rate Prediction
VR	**:** Virtual Reality

LIST OF TABLES

Page

LIST OF FIGURES

Page

A RULE-BASED HUMAN RELIABILITY ASSESSMENT TO ENHANCE SHIP AUXILIARY MACHINERY MAINTENANCE OPERATIONS

SUMMARY

The maintenance operations that carrying out in the engine room are essential for the availability, reliability and smooth running of machinery systems. Thus, maintenance activities should be executed in accordance with a predetermined schedule. In order to standardize this, a planned maintenance schedule (PMS) is widely utilized in the merchant ships. Therefore, the machinery systems should be maintained in accordance with the PMS guidelines. However, these labor intensive actions may end with undesired results due to human errors. Since the human error is responsible for the majority of operational accidents in many industrial domains; estimating the human reliability in accordance with the engine room conditions becomes an important issue. For this reason, human factor studies focus on the more specific, domain based analysis lately.

In industrial working environments, there can be Error Producing Conditions (EPC) which may increase the error likelihood of human actors. The EPC often arise from safety issues which can be detected by a proper analysis during or prior to an operation. In the literature, there are 38 different EPC have been identified within the conventional human error assessment and reduction technique (HEART) method. The method calculates human error probability (HEP) not only with the EPC, but also the generic task types (GTT). For this reason, there are also 9 different GTT have been identified with the comprehensive task descriptions. These comprehensive descriptions make GTT a very convenient parameter for different industrial fields. As a result, industry specific human reliability studies modify the EPC parameters rather than GTT. In the literature, the EPC values have been redetermined for particular domains such as nuclear plants, railways, aviation and maritime.

In the maritime, the EPC values have been adopted in shipboard operations via shipboard operations human reliability analysis (SOHRA). The SOHRA is a special method that could be implemented in all operations on-board a ship. However, maintenance and operational tasks in the engine room involve a vast number of peculiar actions in comparison with the other shipboard operations. The significant discrepancy between the job definitions of the deck and engine room crew is evidence to this question. Seafarers in the deck perform a multitude of tasks on a vessel, but essentially navigate the vessel from the bridge, whilst; engine room officers are responsible for the maintenance and operation of propulsion systems and auxiliary machinery, in addition to other engine room duties. For this reason, an extension of SOHRA which particularly focuses on engine room crew is fundamental to carry out more accurate human reliability analysis. Therefore, operational safety in marine engineering maintenance and operations can be enhanced with more sensitive HEP calculations along with the pinpointly taken countermeasures.

For the reasons mentioned above, this study proposes marine maintenance and operations human reliability analysis (MMOHRA) approach by determining marine engineering specific EPC, as an extension of SOHRA. The EPC in MMOHRA is calculated through meticulously analysed historical data of ship accidents that occurred between 2008-2018. During this phase, there are 1380 ship accident investigation reports are examined and only 70 of them are selected to establish the accident database. The reason of this, there are three important criteria are considered when filtering the investigation reports; i) The accident must be sourced by human error of the engine reeom crew, ii) Accidents should be recent, iii) Accident investigation reports must contain clear evidences. In conclusion, an amount of 435 accident causes is derived from the 70 reports. In the classification phase of accident causes, the human factor analysis and classification system (HFACS) is adopted into marine engineering by suggesting HFACS for marine maintenance and operations (HFACS-MMO) method due to requirement of marine specific new classification layers. In addition to these, a rule based good practice tool of MMOHRA is introduced in order to response EPC and GTT assignment challenge of marine experts. The tool is developed upon a software code which is written through “Python 3” language. Besides, SQLite database is also used in order to embed EPC and GEP values of MMOHRA. Therefore, this tool can be applied to a digital engine room environment to support safety level of a ship.

The MMOHRA is demonstrated with the case studies of ship auxillary machinery maintenance operations, namely; screw pump overhaul, HFO separator overhaul and diesel generator overhaul. Firstly, the MMOHRA is implemented in a three-rotor screw pump overhaul of a general cargo ship. Therefore, the difference between the MMOHRA and SOHRA results are highlighted. Second, the HFO separator overhaul is investigated in five different ships’ conditions via MMOHRA practical calculation tool. Comparison between the results of classical MMOHRA application and good practice tool based application is provided. Finally, a detailed diesel generator overhaul is inspected under PMS conditions via MMOHRA tool. This time, recovery actions for the ship are identified and MMOHRA framework is completely implemented.

Since therefore, this study contributes to the maritime safety literature via proposing meticulously studied significant approaches: MMOHRA and HFACS-MMO. Herein, not only the marine engineering specific EPC values are re-determined but also all descriptions are re-written for marine maintenance and operations. Additionally, the safety deficiencies of accidents that have major impact towards the establishment of HFACS-MMO are highlighted. Besides, safety issues of certain ships are detected and valuable recovery actions are provided via case studies. Moreover, rule based structures for GTT and EPC are discovered and utilized in a software code to create good practice tool of MMOHRA, which can be used by marine experts in marine maintenance and operations.

GEMİ YARDIMCI MAKİNELERİ BAKIM ONARIM OPERASYONLARININ İYİLEŞTİRİLMESİ İÇİN KURAL TABANLI İNSAN GÜVENİLİRLİĞİ ÖLÇÜMÜ

ÖZET

İnsan güvenilirliği çalışmalarının önemli bir kısmı, yapılacak olan operasyonun görev tanımları ve çalışma ortamının koşulları göz önüne alınarak gerçekleştirilmektedir. Çalışma ortamlarında, insan hatalarının meydana gelme olasılığını artıran bir takım hata üreten koşullar (Error Producing Conditions - EPC) mevcut olabilir. EPC'ler genellikle, bir operasyon başlamadan önce veya operasyon esnasında yapılabilecek olan uygun bir analizle tespit edilebilmektedir. Bu nedenle, insan güvenilirlik analizi, birçok sanayi kuruluşunda insan kaynaklı iş kazalarının önlenmesinde önem arz etmektedir. Literatürde, insan hatası değerlendirme ve azaltma tekniği (Human Error Assessment and Reduction Technique - HEART) yönteminde 38 farklı EPC tanımlanmıştır. Bu yöntem, insan hatası olasılığını (Human Error Probability – HEP) iki ana parametreye göre hesaplamaktadır. Bunlardan ilki, biraz önce bahsi geçen EPC; diğeri ise, operasyonel görevlerin türünü tespit etmeye yarayan genel görev türleridir (General Task Types - GTT). GTT, kapsamlı olarak tanımlanmış 9 farklı görev sınıfına göre görevleri kategorize etmektedir. GTT'nin tanımlamaları herhangi bir endüstriye özgü olarak belirlenmediğinden, farklı endüstriyel alanlar için kullanılabilir bir parametre olarak karşımıza çıkmaktadır. Bu nedenle, endüstriyel alan bazında özelleşmiş insan güvenilirliği çalışmaları EPC parametreleri üzerine yoğunlaşarak, özel EPC değerleri tanımlarken, orijinal HEART yöntemindeki GTT değerlerini kullanmaya devam ederler. Literatürde, EPC değerleri nükleer santraller, demiryolları, havacılık ve denizcilik gibi belirli alanlar için yeniden belirlenmiş ve böylece endüstri özelinde insan güvenilirliği analizi çalışmaları ortaya konulmuştur.

Denizcilikte, EPC değerleri, gemi operasyonlarında insan güvenilirliği analizi (Shipboard Operations Human Reliability Analysis - SOHRA) metotuyla yeniden tanımlanmıştır. SOHRA, bir gemideki tüm operasyonlarda uygulanabilecek bir şekilde tasarlanmış, kapsamlı bir yöntemdir. Ancak, makine dairesindeki bakım-onarımlar ve rutin operasyonel görevler, diğer gemi operasyonlarına göre yüksek oranda farklılık gösterir. Güverte zabitlerinin iş tanımları ile makine vardiya zabitlerinin iş tanımları arasındaki temel farklılıklar bu hipotezi doğrulamaktadır. Bu nedenle, makine dairesindeki operasyonlardan doğabilecek insan hatalarının analizi için daha özel bir yaklaşıma ihtiyaç duyulmaktadır. Bu sağlandığı takdirde, gemi bakım-onarımı ve operasyonlarındaki insan güvenilirliği analizi daha hassas ve tutarlı HEP hesaplamaları ile gerçekleştirilebilecektir.

Diğer taraftan, makine dairesinde gerçekleştirilen bakım-onarım operasyonlarının etkin bir biçimde gerçekleştirilmesi, ana ve yardımcı makinelerin verimliliği, güvenilirliği ve dayanıklılığı için büyük önem taşımaktadır. Bu nedenle, bakım-onarım faaliyetleri doğru zamanında yürütülmelidir. Bunu sağlamak için, gemilerde planlı bakım takvimi (Planned Maintenance Schedule - PMS) günümüzde yaygın olarak kullanılmaktadır. PMS'ye göre makineler ve diğer yardımcı sistemler, belirli dönemler ve belirli çalışma saatleri temel alınarak gerçekleştirlir. Ancak literatürde, gemi ortamına uygulanma potansiyeli bulunan bir takım yeni yaklaşımlar mevcuttur. Aslında, bir gemiye yeni bir bakım tekniği uygulamak pek çok zorluğa sahiptir. Buna rağmen, 'dijitalleşme ve denizcilik' konusu akademik ve endüstriyel çevrelerce sık sık gündeme getirilmektedir. Çünkü yakın gelecekte, teknolojik ilerlemelerin ve dijitalleşmenin öyle ya da böyle denizciliği de kapsayacak olması kaçınılmaz olarak görülmektedir.

Özellikle son yıllarda, dijitalleşme olgusu küresel çapta hızla ivme kazanmıştır. Pek çok sektör, giderek yaygınlaşmakta olan ileri teknoloji cihaz ve donanımları etkin bir biçimde kullanmakta ve büyük bir sanayi devrimi için hazırlanmaktadır. Gelişmekte olan teknoloji ve bilimsel yaklaşımların harmanlanmasıyla elde edilen başarılı uygulamalara her geçen gün yeni örnekler eklenmektedir. Dolayısıyla, bir işyerinde çalışan insanların görev ve sorumluluklarının gelecekte ne gibi değişimler yaşayacağı tartışılmaktadır. Genel kanı, operasyonel süreçlerin otomasyonu ile insanların iş yükünün büyük ölçüde azalacağı şeklindedir. Ancak, insan-makine etkileşimlerinin önemli ölçüde değişecek olması nedeniyle bir takım yeni zorlukların ortaya çıkması da beklenmektedir. Bu durum, mevcut emniyet önlemlerinin yeniden şekillenmesine yol açacaktır. İnsan hatası, iş kazalarının çoğundan sorumlu olduğu için; insan güvenilirliğinin gelecekteki koşullara uygun olarak tahmin edilmesi daha da önemli bir hale gelmektedir. Bu nedenle, insan güvenilirliği konusundaki yeni çalışmaların, günümüz şartlarına ek olarak; yakın gelecekteki endüstriyel şartların emniyet faktörüne olan etkilerine yönelik daha doğru tahminler ve öneriler yapmak üzere dijital ortamlara daha çok odaklanmaları beklenmektedir.

Yukarıda belirtilen nedenlerden dolayı bu çalışma, 38 adet EPC parametresini SOHRA'nın bir uzantısı olarak yeniden belirlemekte ve böylelikle özelleştirilmiş gemi bakım-onarım ve operasyonları insan güvenilirliği analizi (Marine Maintenance and Operations Human Reliability Analysis - MMOHRA) yaklaşımını sunmaktadır. MMOHRA'daki EPC değerleri, 2008-2018 yılları arasında meydana gelen gemi kazalarının titizlikle incelenmesi ve emniyet hatalarının derlenerek ortaya çıkarılması sonucu elde edilen veriler aracılığıyla hesaplanmıştır. Bu aşamada, 1380 gemi kazası inceleme raporu dikkate alınmış ve bunlardan sadece 70'i tezin veritabanına uygun bulunmuştur. Bunun nedeni, raporların seçimi aşamasında üç önemli kritere hassasiyet gösterilmiş olmasıdır, bunlar; i) Kazanın makine dairesi kaynaklı insan hatası nedeniyle meydana gelmiş olması, ii) Kazaların güncel olması, iii) Kaza soruşturma raporlarının güvenilir olup somut çıkarımlar yapılabilecek nitelikte olmasıdır. Sonuç olarak, 70 rapordan 435 kaza sebebi ortaya çıkarılmıştır.

Kaza nedenlerinin sınıflandırma aşamasında insan faktörü analizi ve sınıflandırma sistemi (Human Factor Analysis and Classification System - HFACS) kullanılmak istenmiş, ancak kaza sebepleri incelendiğinde denize özgü yeni sınıflandırma sisteminin gerekli olduğu sonucuna varılmıştır. Bu nedenle, gemi bakım-onarım ve operasyonları için HFACS (Human Factor Analysis and Classification System for Marine Maintenance and Operations - HFACS-MMO) yöntemi önerilmiştir. Ek olarak, MMOHRA'nın uygulama aşamasında, uzmanların EPC ve GTT atama zorluklarına yanıt vermek amacıyla kural tabanlı bir hesaplama aracı geliştirilmiştir. Bu araç, "Python 3" dilini kullanarak pratik insan güvenilirliği hesaplaması yapmaya elverişli bir yazılımdan oluşmaktadır. Bu nedenle, geliştirilmeye açık olan bu araç, gelecekte bir geminin emniyet seviyesini destekleyebilecek nitelikte, dijital ortamlarla uyumlu olabilecek bir biçimde tasarlanmıştır.

Daha sonra, MMOHRA yöntemi gemi yardımcı makineleri bakım-onarım operasyonlarına uygulanarak gerçek gemiler üzerinde gösterimi gerçekleştirilmiştir. MMOHRA üç farklı yardımcı makine işlemi üzerine uygulanmıştır; i) Vidalı pompa bakım-onarımı, ii) Ağır yakıt seperatörü bakım-onarımı ve iii) Dizel jeneratör bakım-onarımı. İlk saha çalışmasında MMOHRA, bir genel kargo gemisinin üç vidalı pompası üzerine uygulanmış ve SOHRA ile arasındaki farklar vurgulanmıştır. Ağır yakıt seperatörü bakım-onarım operasyonunda ise MMOHRA; kural tabanlı hesaplama aracı yardımıyla beş farklı gemiye ayrı ayrı uygulanarak farklı gemi koşullarında insan güvenilirliği analizini gerçekleştirilmesini sağlamıştır. Ayrıca, bahse konu hesaplama aracı olmadan, eski yöntemle de hesaplanmış ve sonuçlar arasında karşılaştırma yapılmıştır. Son olarak, bir dizel jeneratör bakım-onarım operasyonuna uygulanmış ve PMS koşulları altında insan güvenilirliğini sorgulamıştır. Bu kez, gemi için emniyet tedbirleri gözden geçirilmiş ve emniyet zafiyetlerinin giderilmesinde etkin rol oynanmıştır. Buna ek olarak, inovatif bir takım değişiklikler önerilmiş, daha dijital bir makine dairesi ortamının makine zabitleri üzerindeki uzun vadeli potansiyel etkilerine dikkat çekilmiştir.

Sonuç olarak, bu çalışma titizlikle elde edilmiş önemli yaklaşımlar sunarak, denizcilikte emniyet literatürüne önemli katkılar sağlamaktadır. Bunlardan en önemlileri; MMOHRA ve HFACS-MMO yaklaşımlarıdır. Burada, sadece makine dairesinde kullanılacak olan rakamsal EPC değerleri yeniden belirlenmemiştir, aynı zamanda tüm EPC tanımlamaları gemi bakım-onarım ve operasyonları için yeniden ifade edilmiştir. Ayrıca, HFACS-MMO'nun oluşturulmasına büyük etkisi olan kazaların güvenlik eksiklikleri vurgulanmış, geçmiş kazalardaki emniyet zafiyetleri tartışılmıştır. Buna ek olarak, saha çalışmalarıyla birçok geminin emniyet sorunları tespit edilmiş ve etkin çözümler önerilmiştir. Ayrıca, denizcilikte uzman kişiler tarafından gemi bakım-onarım ve operasyonlarında kullanılabilecek pratik MMOHRA hesaplama aracı oluşturulmuş ve endüstriye kazandırılmıştır.

1. INTRODUCTION

Propulsion of a ship strongly depends on availability and reliability of machinery systems. A well timed and effective maintenance provides safe, smooth and efficient shipping operations. In a ship engine room, where the various machines and equipment are located, engineers and crew carry out numerous maintenance duties. In this context, the most commonly used maintenance approach on-board a ship is planned maintenance schedule (PMS). A planned maintenance system enables shipowners and operators to plan, perform and document the maintenance of vessels at intervals that meet the requirements of the class and the manufacturer. In addition to complying with all relevant legislation, the main goal is to ensure safe and effective vessel operations, including working environment. Depending on the size and complexity of the shipping company and the types of vessels in operation, PMS can show some variance. However, for all cases; a comprehensive maintenance strategy which is based on risk management is applied by establishing a schedule for the machinery, equipment and fittings. In compliance with the International Safety Management Code (ISM), a scheduled maintenance scheme is compulsory on ships. An effective planned maintenance system not only helps to meet the safety and environmental goals set out in the ISM Code, but is also an investment in asset protection and management optimisation. The aim of the PMS for shipboard operations has more than one objectives. PMS provides a schedule to all maintenance operations in order to monitor which of the engine room tasks must be done, completed or not completed. Therefore, PMS keeps all engines, machinery and engine room components in adequate level at all times, avoid stoppages and maintain speed and consumption requirements of charter parties. PMS also attempts to prevent job disruption by presenting wide perspective to cover all of the operations. Furthermore, PMS describes a clear dividing line between onboard and shore maintenance work.

However, PMS has also some disadvantages such as involving many unnecessarily tasks to be completed by the crew, who have already overloaded with numerous engine room duties. In addition, since this classical approach is not so convenient with digitalized working environment, the operations should be executed by the human centered activities. Since PMS is highly dependent on human effort, human reliability become an important issue. For this reason, human factor should be examined substantially considering the crew duties and responsibilities of PMS.

Nevertheless, the digital revolution is reshaping the world and the maritime sector is a part of this transformation. In this sense, the digitalization and the use of data can be a huge impact on shipping activities. Sensor hubs, data generators, data transmission, cloud based systems and advanced softwares can enable rapid and effective information exchange between system components and human actors in the engine room. Eventually, new maintenance approaches would be implemented to the ships via taking advantage of these digital information flows in the near future. As a consequence, the role of human actors on-board a ship can change essentially, so; the concept of human reliability should be also examined with this perspective in order to reveal advantages and disadvantages of the digital transformation for the ship maintenance and operations. For this reason, once an analysis of human factor should be done, then recovery actions should be proposed in accordance with the necessities of existing conditions as well as making suggestions in terms of permanent innovations for a working environment which benefit from the most proper digital instruments. Therefore, more effective countermeasures to be taken in the future can be suggested towards safety issues in addition to the immediant actions, which aim only the “saving the day” in a short time for certain operations.

Nevertheless, a substantial digitalization of vessels has very challenges to come true. These challenges can be listed as (Kandemir and Celik 2017a):

- Ships are operating in ever changing conditions, so data acquisitioning becomes more difficult job.
- There are plenty of strict norms of administrative bodies, classification societies and other organizations in maritime sector thus; international conventions should allow such integrations.
- Crew is unskilled for these kind of innovations and they are already overloaded with the STCW based trainings.

- There are uncertainties in the integration process due to several different ship types.
- Unwillingness of ship owners towards substantial innovative integrations due to financial concerns.
- Different ship characteristics can retard the know-how process which can be conveyed from experienced ships to the new ones.

For the reasons mentioned above, substantial innovations may require plenty of time to make realize through necessary implementations on-board ships. Hence, instead of general recommendations, case specific feasible suggestions can take place for a particular organization. Therefore, operational safety can be increased permanenetly for on-board a ship as well as offshore working places. In this sense, the role of human actors, operational requirements, case specific conditions and existing technical capabilities should be identified clearly and accurately. In order to actualize this, a detailed research which considers this subject from many aspects is required.

1.1 Motivation

A great number of studies have proven that the human error is dominant factor which causes a wide range of accidents and incidents in many industrial facilities (Kumar et al, 2017; Kandemir and Celik, 2020). According to Di Pasquale et al. (2015), the estimations of human error ratings in road transportation is 85% of all failures, 70-80% in aviation, 60-90% in chemical industry, 50-70% in nuclear power plants, and 80-85% in shipping activities. Herewith, researchers have been studying active and latent causes of human errors in attempt to identify underlying reasons of these consequences (Wang et al, 2013; Zarei et al, 2019). Such consequences usually addressed as accidents, which could be a variety of maleficence to the human health, machinery, equipment or marine environment (Ugurlu et al, 2018). When the severity of an incident increases, damage usually intensifies significantly. In this regard, incidents that have occurred over the past few years have been reviewed and analysed by the experts to determine whether additional countermeasures can be implemented to improve operational safety. The countermeasures may be variable such as the introduction of new laws, the incorporation of technical technologies, the enhancement of working environment conditions and the implementation of new training programs.

The success of the application, however, depends very on the sophistication of established information about the human element. Since the human error may arise from several factors of a sector’s characteristcs, an industry specific human factor analysis should be carried out (Celik and Cebi, 2009).

In the maritime industry, safety is a vital issue for many reasons. In any case, ships operating at sea can be very vulnerable to significant losses because there are few options available for repair and recovery operations. As a spectacular example; the disaster of the well-known *Titanic ship (1912)* caused around 1500 passengers to die and resulted in the ship's complete loss (Khurana, 2017). The impact of this tragedy was so momentous, that the International Convention for the Safety of Life at Sea (SOLAS) has been adopted in response to this disaster by International Maritime Organization (IMO) in 1914. This convention has been updated many times until today and by 1980 the new edition, so-called "SOLAS'74," has been entried into force. (IMO, 2019). The purpose of this convention is to ensure that merchant ships in the design, equipment and service processes comply with the minimum safety standards. The *MS Herald of Free Enterprise* accident in 1987 which caused 193 deaths has raised consciousness of various aspects of human error. Therefore, IMO has annexed the International Safety Management (ISM) Code to the SOLAS in attempt to contribute to the safe navigation of ships regarding human and organizational factors (Schröder-Hinrichs et al, 2013). In detail, certification, familiarization, training and communication are recognized as core aspects within the resources and personnel clause of the ISM Code. The Code also discusses the creation of plans and procedures for essential shipboard operations, as well as the designated person ashore, operations manager and related marine superintendents, to ensure that they control the implementation accordingly (Kandemir et al, 2017a).

In accordance with the ship type and course of events, the maritime environment may also be greatly impacted. To exemplify, the oil spill of the disaster of *Torrey Canyon* crude oil tanker ship has killed more than 25000 seabirds and a significant number of marine species with an oil spill of 119000 metric tonnes in 1967 (Duda and Wawruch, 2017; Wells, 2017). Another example is *the Argo Merchant* ship crash in 1976, which accounted for around 28000 metric tonnes of oil spill near Puerto La Cruz, Venezuela (Gundlach, 2013). As another major accident, *Exxon Valdez* tanker ship scattered about 37000 metric tonnes of crude oil in Alaska, 1989 (Talley et al, 2001). All of these incidents were played a significant role in additional legal countermeasures such as the International Convention for the Prevention of Pollution from Ships (MARPOL). The purpose of this Convention is to conserve the marine environment in an attempt to eliminate oil contamination and other harmful ingredients and to reduce the accidental spillage of these substances (IMO, 2019).

The IMO has legislated a large range of preventive laws, such as Standards of Training, Certification and Watchkeeping for Seafarers (STCW). The STCW Convention came into effect in 1978, and was periodically revised as the last amendment was introduced in 2010. The *Torrey Canyon* disaster was one of the main sparks behind STCW. The STCW convention aims to set global standards for the training, certification and monitoring of seafarers in a common agreement (Kandemir and Celik, 2017b). The strict norms of STCW have been broadly accepted by the nations which are representing more than 99% of world shipping tonnage. While technical advancement and other safety precautions were taken over several years, human error and organizational failures continue to cause accidents. Only between 2011 and 2016; 600 fatalities, 5607 injuries, and 253 total loss of ships based upon 16539 casualties have been recorded (EMSA, 2017). The number of casualties means safety is still one of the maritime's big concerns and further research is needed.

The most commonly used maintenance approach on-board a ship is PMS. Since PMS is highly dependent on human effort, human reliability and ergonomics become a significant topic. Such responsibilities are directly connected with the critical technical aspects which allow the machinery or equipment up do date and reliable. Thus, inadequate maintenance operations can lead serious implications for ships such as “emergency situations”.

In addition to the PMS, literature contains some advanced maintenance methods such as predictive maintenance, condition-based maintenance, reliability centered maintenance, e-maintenance, maintenance 4.0 and integrated maintenance. In general, these innovative approaches aim to manage a maintenance strategy by focussing on certain specific aspects that are given priority. For example, preventive maintenance focuses on the actual state of specified system components, and optimizes the schedule of maintenance. To do this, system parameters such as vibration, strain, flow, or voltage etc. are controlled continuously by the maintenance system (Raza and Ulansky, 2016). Therefore, the life cycle of vital equipment should be maximized because the intention is to reduce unintended breakdowns. One of the best advances in predictive maintenance is condition-based maintenance approach, as integrated vibration analysis, acoustic emission, ultrasonic testing, oil analysis, strain calculation, electrical impact, shock pulse system, radiographic inspection and thermographic monitoring technologies can be integrated into an existing system (Marquez at al, 2012). Therefore, system status is continuously monitored and if the state of a system component reaches an undesired level, then repair or replacement activities are started after a controlled shutdown.

With the advent of new technologies such as remote diagnostic systems, information & communication technology, automation systems and enhanced data exchange; maintenance finds opportunities for performing even more effective, responsive, simple, adaptive and reliable maintenance. In this sense, recent maintenance strategies, newly developed expensive systems, smart machines, autonomous devices and software are certainly valuable enhancements to the maintenance activities at management level. These developments, however, still need a lot of work to get a broad understanding of true potential for ships. At this level, despite substantial technological advancements; the actual maintenance workload is likely to depend on human assistance as it has always been. Accordingly, human reliability remains as a critical aspect of operational safety especially in maintenance operations.

1.2 Research Requirements

The ship accidents can vary as they may result in collision, grounding, capsizing, flooding, fire, explosion, man overboard emergency situations. Since the main reason is human error, the crew’s duties and responsibilities should be thoroughly researched. Indeed, a ship crew consists of two main divisions onboard: “deck department” and “engine room department”. Seafarers on the deck carry out a number of tasks, but essentially navigate the vessel from the bridge, while engine room officers are responsible for the management and maintenance operations of the propulsion and auxiliary systems in addition to other watchkeeping duties in the engine room. Since the task descriptions of these two units totally different, causes of accidents may be originated from deck or engine room, or both.

The researchers usually classify ship accidents with respect to the types of accidents (i.e: collision, explosion, grounding…), ship types (i.e: tanker, bulk carrier…), or specific regions. Nonetheless, recent ship accidents have shown that the engine room related accidents are sourced from certain particular forms of human error. However, contrary to the common opinion, such errors not only lead to fire or explosion in the engine room but also lead the vessel to collision, grounding, and other types of accidents. As an illustrative case, the accident of *Dumun bulk carrier* has grounded in 2011 by the malfunction of steering gear, which is under the responsibility of the engine room crew (ATSB, 2012). Similarly, *Conmar Avenue* container ship has collided due to the main engine lubricating oil system failure in 2013 (BSU, 2013). (See also: *Isle of Arran (2010), MSC Basel(2010), Langballid (2014), Norfolk Express (2014), BOW Singapore (2015)…*).

On one hand, a ship engine room has challenging conditions for marine engineers in terms of being hot, noisy, vibrant, humid, narrow and complex places so error probability of ship engine room crew should be measured rather differently (Kandemir and Celik, 2017b). On the other hand, the human element is very conclusive for availability of critical engine systems and equipment, and this is very dependent on the smooth execution of operational and managerial tasks. In this regard, an advanced ship engine room-specific human reliability analysis should be researched in order to conduct more reliable error probability predictions for ship engine room crew. For this reason, the accident causes such as safety issues, deficiencies and other findings of the past engine room sourced ship accidents or recent adequate data are required. Therefore, more accurate HRA can be made. Besides, more effective recovery actions can be proposed to the marine maintenance operations as well as more innovative suggestions can be made by taking the potential benefits of technological developments into account.

1.3 Research Organization

For the mentioned reasons above, this paper studiously investigates most recent engine room crew based ship accidents which have been occured between 2008 and 2018. As a systematic approach, Human Factor Analysis and Classification System (HFACS) is taken into account. Eventually, Human Factor Analysis and Classification System for Marine Maintenance and Operations (HFACS-MMO**)** is proposed by modifying the original HFACS. Moreover, marine maintenance and operations specific Error Producing Conditions (mmo-EPCs) are defined as an extension of existing Shipboard Operations Human Reliability Analysis (SOHRA) to be utilized in marine maintenance and operations. Furthermore, a rule based practical human error probability (HEP) assessment tool is proposed by taking advantage the identified mmo-EPC values.

To conclude, this study which is entitled as “A Rule-Based Human Reliability Assessment to Enhance Ship Auxilliary Machinery Maintenance Operations” presents a rule based human reliability assessment method in order to measure marine maintenance and operations specific human error probability on ship auxilliary machinery related engine room tasks (See: Chapter 3). Later, in the next chapter; the proposed approach is demonstrated via three different case studies regarding the ship auxiliary machinery maintenance operations. Firstly, the MMOHRA is implemented in a three-rotor screw pump overhaul of a general cargo ship. Herein, the difference between the MMOHRA and SOHRA results are highlighted. Second, the HFO separator overhaul is investigated in five different ships’ conditions via MMOHRA practical calculation tool. Comparison between the results of rule based MMOHRA and classical MMOHRA is also provided. Finally, a detailed diesel generator overhaul is inspected. This time, recovery actions are identified and MMOHRA framework is completely implemented. All discussions are made under relevant sections of each case. In addition, the conclusion of the research is given in chapter 5 and a comprehensive review, limitations and further studies are discussed accordingly.

2. LITERATURE REVIEW

The definition of the "human error" can be variable depending on perspectives of researchers, however; the common view signals the unintended failures or deficiencies made by the human actors due to the presence of one or more circumstances that cause errors. Human error may occur if the system performance limits are exceeded by human activities to unreasonable levels (Kirwan, 1994). For this reason, most of the studies examine "human error" sophisticatedly by including human performance errors (Kandemir and Celik 2020). In this regard, an "Error Producing Condition (EPC)" indicates the existence of a condition which increases the likelihood of human error in a working environment (Williams, 1988). For this reason, the reliability of humans in an industrial process is also supervised in the well-organized companies by appropriate supervisors. In this context, human reliability can be defined as the rate of the likelihood of human error, which shows how reliable or unreliable an authorized person may be during a given task (Pyy, 2000). As another definiton, human reliability is the probability that humans perform different tasks satisfactorily (Calixto, 2016). However, reliability of human is very dependent on the EPCs. About this subject, EPCs can be arisen from working environment, organisational management, safety culture, equipment design or another aspect in an organization.

2.1 HRA Studies

In the literature, there are some advanced methods that suggest EPCs to quantify performance shaping factors to estimate the probability of human error. The EPCs are important values that should be used in calculating the likelihood of human error in many human reliability analysis (HRA) studies. There are 38 different EPCs described in the original HEART (Williams, 1988). However, recent studies have proven that specific EPC values can be very useful to conduct more accurate human reliability analysis in different fields. On that account, in nuclear industry; Nuclear Action Reliability Assessment (NARA) (Kirwan et al, 2004), in aviation; Controller Action

Reliability Assessment (CARA) (Kirwan and Gibson, 2007), and in railway transportation; Railway action reliability assessment (RARA) (Gibson et al, 2013) have been intended. In the maritime, Akyuz et al. (2016) have identified EPCs through SOHRA for ship operations. The SOHRA is a specific approach for performing a human reliability study on board a ship, but it provides a wide viewpoint for all shipping activities, requiring an expanded version for maintenance and operations in particular.

In addition to these, there are various human reliability quantification approaches can be found in the literature with different contexts. Many of these methods include HEP estimation in an effort to obtain a possible failure level for an assigned task (Kirwan, 1994). A Technique for Human Error Analysis (ATHENA) contributes to the HRA studies by offering a comprehensive framework to identify human behavior that may result in their success or failure (Cooper et al, 1996). Technique for Human Error Rate Prediction (THERP) consists of four phases to predict HEP values: i) familiarization, ii) qualitative assessment, iii) quantitative assessment, and iv) incorporation. Performance Shaping Factors (PSFs) and their influence can be identified through probability trees and dependence models in THERP (Kirwan, 1996). Human Error Assessment and Reduction Technique (HEART) takes nine Generic Task Types (GTTs) and thirty-eight EPCs into account to calculate HEP values (Williams, 1998). The Success Likelihood Index Methodology (SLIM) is another comprehensive technique in human reliability studies. The analysis phase takes advantage of a variety of muster sequences. The SLIM transforms various PSFs of an operation into an index; a single value (Embrey, 2000). PSFs are usually utilized to estimate HEP such as the Analysis of Consequences of Human Unreliability (ACIH) proposed by (Vanderhaegen, 2001). The ACIH presents a non-probabilistic approach for human reliability assessment, so it can be utilized when a qualitative integration of human error into risk analysis is applicable. This method can also be benefitted for assessing the consequences of intentional human errors such as violations or removing the barriers that intended to prevent accident severity (Vanderhaegen, 2010). There can also be some conflicts between the human viewpoints towards a system design, which is called as “dissonances”. Dissonances should be monitored properly by controlling and reinforcing the gaps of different actors’ knowledge (Vanderhaegen and Carsten, 2017). Thus, different aspects of human nature can be regarded in an effort to achieve more objective results from risk analysis studies (Vanderhaegen, 2014).

The HRA studies have been applied in various domains such as nuclear power plants (Hirotsu et al, 2001; Jang et al, 2013), engine systems (Chang et al, 2010), electronic systems (Liang and Wang, 1993), the defense industry (Hausken, 2008), manufacturing (Bertolini et al, 2010), spaceflight (Calhoun et al, 2014), traffic safety (Taga et al, 2012), and aviation (Rashid et al, 2014). According to this picture, there have been a variety of HRA studies which focus on different aspects on human reliability. The majority of these methods can be labelled as "empirical studies" such as THERP (Swain and Guttmann, 1983), SLIM (Embrey et al, 1984), ATHEANA (Cooper et al, 1996), HEART (Williams, 1988), Cognitive Reliability and Error Analysis Method (CREAM) (Hollnagel, 1998), Simplified Plant Analysis Risk Human Reliability Assessment (SPAR-H) (Gertman et al, 2005) and Performance Shaping Factor Based Human Reliability Assessment Using Valuation-Based Systems (PRELUDE) (Rangra et al, 2017). On the contrary, stochastic approaches such as Bayesian Network (Almond, 1992) are difficult to adopt to take principle of HRA into consideration. For this reason, such studies appear relatively less when comparing the empirical studies.

HRA has also been studied by several researchers in the maritime industry, as it is the primary cause of most marine incidents and accidents; the maritime authorities have introduced various regulations to reduce human error-based incidents (Kandemir et al, 2015). Even so, studies show that accidents of this kind still occur in the maritime sector (Akyuz, 2017; Gaonkar et al, 2011; Akyuz et al, 2018). In this regard, there are many studies that concentrate on HRA issues by taking advantage of various methodological approaches. One of these studies is Yang et al. (2013), as they apply a modified CREAM method by adopting a Bayesian reasoning model. The method was examined via a scenario which postulates a shutdown failure over an oil tanker cargo oil pump. Likewise, Martins and Maturana (2013) executed an HRA utilizing the Bayesian belief networks on ship collision accidents. Similarly, Musharraf et al. (2013) applied a Bayesian network for an emergency situation in an offshore environment. In addition, Ung (2015) combined fuzzy logic and the CREAM method to investigate HRA over an oil discharge procedure on tanker ships. Moreover, Xi et al. (2017) used the CREAM method with the evidential reasoning method and Decision Making Trial and Evaluation Laboratory (DEMATEL) technique to quantify HEP and presented findings by means of a case study. Furthermore, Akyuz (2015) presented a risk-based CREAM model to quantify HEP over a gas inerting process of crude oil tanker ships. In furtherance, Akyuz and Celik (2015a) executed an empirical study and proposed a novel technique for HRA on a tank cleaning process on-board a chemical tanker ship via merging HEART and AHP. (Akyuz and Celik, 2015b) also suggested a quantified HRA for on-board loading of LPG tanker vessels by using a CREAM method to classify marine-specific cases. In addition, the SOHRA method is intended as a marine specific approach for ship operations by Akyuz et al. (2016). In particular, Noroozi et al. (2013) conducted a HRA study in maintenance operations for offshore oil and gas facilities. Similarly, Islam et al. (2016) and Islam et al. (2017) also conducted a study to quantify human errors on marine maintenance operations. Correspondingly, Okaro and Tao (2016) researched HRA over subsea compression systems.

2.2 Studies on Maintenance Operations

Maintenance is a mandatory activity for industrial organizations to maintain and preserve machinery, equipments, replaceable parts, hardwares and other devices. Any failure caused by poor maintenance policy causes hazard over a planned workflow and task schedule. Depending on the type of organization and sector vulnerability, any failures can lead to extremely costly consequences. As newly built, costly processing systems are becoming more common in a working environment, more investment is needed in maintenance departments. As a result, the maintenance departments are allocated 30 per cent of the total workforce in the chemical industries (Jonge at al, 2017). Therefore, maintenance approach has a major role for companies in achieving business goals in a smooth and efficient manner.

There are various maintenance methods in the literature and these are mostly classified as corrective maintenance (CM) and preventive maintenance (PM) into two categories. CM is a maintenance operation that focuses on fixing or mending the failed component of a device or equipment (Drenthe, 2019). This process may involve more than one recovery method, such as isolation of malfunctions, decomposition, replacement, re-installation, modification, verification and fixation of the relevant failed elements (Fang and Zhaodong, 2013). Hence, malfunction time, detection and recovery time of a malfunction and the cost of malfunction could be considered for future operations.

In run to failure (RTF) maintenance approach, the relevant part, equipment or machinery is simply allowed to the failure. If the problem starts to interfere with system functionality, then repair & replace processes are carried out (Piatrowski, 2001). This approach is recommended when there is no serious effect of operational shutdowns on productivity and cost of equipment is not significant.

PM is a routine review that concentrated on detecting an incipient malfunction. Time-based maintenance schedule is usually designed to prevent unnecessary shutdowns; therefore, system efficiency is intended to be maximised (Chalabia et al, 2016). Different adapted PM methods were researched, developed or combined with other maintenance techniques in the literature, depending on the system characteristics. In the maritime, PMS is utilized as a form of PM. PMS enables necessary actions to be carried out in accordance with requirements of international maritime conventions and classification societies. Since PMS represents an actual workload for the crew of a ship, specific tasks must be performed properly at the right time. In PMS, time-based schedules and running hour-based maintenance activities are intended to be maintained with the aim of avoiding potential risks that may result in breakdowns (Anantharaman et al, 2019). That means that any machinery or equipment that is part of a PMS checklist must be maintained even if there is no expected failure. These maintenance operations and PMS checklists are properly registered and maintained when conducted by responsible staff to meet the requirements of the ISM Code (Kandemir and Celik, 2017a).

Despite these advantages of PM implementations, catastrophic failures are likely to occur and PM practices are generally criticized as labor-intensive activities due to involvement of several unneeded maintenance operations (Baba and Avadhani, 2019). To eliminate these drawbacks and improve process performance, Predictive Maintenance Method (PDM) have been applied in most industrial plants. Notwithstanding a scheduled operation, the PDM differs from PM by concentrating on the actual state of specified parts of a system. In this sense, responsible experts must monitor technical aspects and physical parameters such as vibration, pressure, flow, or voltage in PDM (Raza and Ulansky, 2016). This aims to optimize the service life of equipment while reducing unintended breakdowns and the probability of system operation failure (Baidya and Gosh, 2015). In this sense, the approach to condition-based maintenance (CBM) comes to prominence as an important PDM technique

(Lazakis and Ölçer, 2016; Tan et al, 2020). Currently, vibration analysis, acoustic emission, ultrasonic testing, oil analysis, strain measurement, electrical effects, shock pulse system, radiographic inspection and thermographic monitoring technologies are used to properly analyse CBM data (Marquez at al, 2012). If the condition gets below a defined system level, then the process of repair or replacement starts after a managed shutdown, according to the data obtained.

Nevertheless, as the scope of "maintenance" covers a large range of different fields in the global industry; even the new maintenance strategies may have certain ambiguities for a particular character of the program. Consequently, convergence of all previously mentioned maintenance strategies can be utilized in order to achieve more successful operational outcomes. Reliability centered (or based) maintenance (RCM), for example, advocates a theory of mixed maintenance methods in combination with root cause analysis. Hence, RCM produces a conceptual alghoritm or software system that focuses on most likely failure modes (Yssaad et al, 2012; Dronen, 2019). If more than 20-25 per cent of the maintenance workload is arisen from operational breakdowns, the RCM method could benefit the overall process (Vera-Garcia et al, 2019).

With the advent of emerging technologies such as remote diagnostic systems, the idea of e-maintenance has taken center stage since 2000. E-maintenance offers an opening and extensive coverage of information and communication technologies for multinational businesses participating in the world's innovative manufacturing activities. Successful e-maintenance strategy applications can bring system reliability benefits while integrating customers and suppliers with zero downtime performance (Chowdhury et al, 2012).

Ever-growing technical developments in automation systems and data sharing have provided an opportunity to bring a new idea through more innovative principles of maintenance. Many manufacturing environments consider maintenance 4.0 as one of the most prudential topics emerging from the term "Industry 4.0." In industry 4.0, the key concept is to achieve higher quality efficiency, minimize downtime, maximize energy usage and reduce overall maintenance costs through the interoperability of IoT, IoS and IoP (Zezulka et al, 2016). In addition, by means of CPS, equipment, sensors, software, products, supply chain elements and customers are connected together, so that the basic elements of a network can exchange information in order to carry out control operations independently (Qin et al, 2016). Thus, the term of "industry 4.0" has become the most popular topic in recent studies, calling it the fourth industrial revolution with the industry 4.0's anticipated marginal effect (Kagermann et al, 2013). In this industrial transition, the maintenance 4.0 plays a significant role in contributing to the maintenance standard of the future systems. Further, maintenance 4.0 lies at the core of Industry 4.0 due to new maintenance requirements of complex systems, smart machines, autonomous devices and instruments.

Even though these are early stages of maintenance 4.0, the future capabilities are now widely discussed. So the highlighted technical advances offer a clear understanding of the benefits of this phenomenon. For example, critical parts of a ship could be monitored with multiple failure modes such as noise, vibration, temperature, oil leakage, sudden suspension, failure to start, structural deficiency, irregular fluid viscosity, and indicator malfunction via newly developed sensors and cloud based systems (Kandemir and Celik, 2017b). The latest developments in censor functionality not only allow effective monitoring of the condition but also transform sensor capabilities as they can receive, transmit, elaborate data and transfer commands through digital channels (Ye et al, 2015). For instance, RFID (radio frequency identification) technology is one of the most commonly used tools for these tasks, because it can automatically help data sharing and data storage in a given local area (Chiou and Chang, 2018). Smart sensors and cloud systems need a data transmitter to translate the data collected into readable indicators. For instance, Uhlmann et al. (2017) executed a research on decentralized data analytics to propose a data analysis structure in order to enhance maintenance operations via integrated sensor networks. Sometimes, censors can not be able to incorporate data, so additional systems may be required such as SCADA (Supervisory Control & Data Acquisition Systems) (Nazir et al, 2017). For example, Wang (2016) interrogated intelligent PDM 4.0 and proposed the potential advantages of a maintenance 4.0 based scenario. In maintenance 4.0, therefore, the state of the system is monitored through digital devices by approved staff, even if they are not in their office or work area thus a coordinated network between humans and machines can be provided. By means of maintenance 4.0, a big data based cloud infrastructure is developed to handle the accumulated data within the entire network. CPS can carry out certain maintenance activities through efficient data management. However, there has been no systematic research on CPS incorporation into on board ship maintenance operations. Nevertheless, technological devices such as Augmented Reality (AR), Virtual Reality (VR), digital mobile devices and tablets are more functional than the past, so they support to promote operators' maintenance actions (Masoni et al, 2017; Kandemir and Celik, 2017a). Because of these advances, 3D virtual simulations enable operators to perform maintenance tasks in a virtual environment before executing them in real life (Caputo et al, 2018).

About this subject, Sipsas et al. (2016) performed a case study to determine the maintenance 4.0 capabilities and utilize it as a method for maintenance operators to support their decision making process. In this regard, Rowen et al. (2019) proposed an approach through wearable AR displays in order to contribute operational safety in critical systems. According to this study, responsible engineers can take advantage of real-timed, visual and dynamic information so it supports their decision making actions while providing high situational awareness on duty. Furter, Petersen (2019) has implemented AR devices to the maintenance process by establishing an interactive engine documentation system to make enable rapid troubleshooting actions.

About maintenance 4.0, scenario based studies can also be conducted. To exemplify, Bokrantz et al. (2017) researched a detailed maintenance 4.0 scenario utilizing Delphi approach. By a similar approach, Kandemir and Celik (2017b) also studied the maintenance 4.0 problems for the conversion process to ships, taking into account the various circumstances of old and new merchant ships. Al Najjar et al. (2018) have investigated the most suitable maintenance methods which can be integrated into maintenance 4.0 via Multi-Criteria Decision Making (MCDM) techniques. They realized that the most suitable approaches the ones which can provide comprehensive and dynamic system monitoring advantages such as CBM. Moreover, Taylor et al. (2019) have examined the concept of “digital twins” which means a virtual representation of a real-world based data as a critical aspect of industry 4.0 approach. They compare manufacturing and maritime domains to identify requrements, challenges and specific implementation strategies.

2.3 Criticial Review

The maintenance approaches and their integration into various techniques such as Bayesian approach, Analytic Hierarchy Process (AHP), MCDM can be seen in many industry specific studies which keep this research field recent and up to date. Apparently, one of the main problems of maintenance literature is that there is no standard classification of the various techniques. The classifications and descriptions can show variety between research papers, industrial fields or perspective of researchers. Hence, the maintenance literature looks dispersed as well as limited for domain specific studies.

Nevertheless, there are some valuable industrial implementations of various maintenance strategies in the maritime field. For instance, the study of Lazakis et al. (2016) aims to enhance maintenance monitoring process of ship structures and machinery through new technological instruments such as smart sensors, softwares and computational tools. Similar studies have been researched to support ship maintenance operations on-board a ship with the integration of fuzzy multiple attributive group technique (Lazakis and Ölçer, 2016), fault tree analysis and artificial neural networks on ship main engine (Lazakis et al, 2017), hybrid decision making methology to reveal optimum maintenance strategy (Emovon et al, 2015). Moreover, in order to response classification problem of marine maintenance, Eruguz et al. (2017) presented a classification of the maintenance and service logistics literature considering the key characteristics of maritime sector.

When HRA literature is examined, there are numerous studies can be seen which have been conducted for many domains. Apparently, HRA studies are scarce in the ship maintenance and operations. However, there are some considerable papers exist to be highlighted such as Kandemir et al. (2019). They have assessed the likelihood of human error in different ships' fuel oil separator maintenance operations to identify safety issues of these vessels. The authors have executed HRA for marine engineering considering different aspects of maritime industry. For instance, the effect of environment over human reliability is researched by Abaei et al. (2017). They have conducted a human error risk assessment study for ship maintenance operations considering the harsh environments. They analysed the influence of environment on human actors to contribute risk assessors' efforts. Similarly, Islam et al. (2018) have also executed a research study to identify the most effective environmental factors on human performance.

In addition, some researchers have examined the potential advantages and disadvantages of technological developments on marine engineering human reliability. To exemplify, Allal et al. (2017) have carried out a HRA considering the autonomous ship conditions through sea chest cleaning operation and discussed the potential benefits of this type of ships. Similarly, Kandemir and Celik (2020) have conducted a HRA on a ship auxiliary machinery overhaul considering the existing ship PMS environment. Later, they have conducted another HRA on the same equipment with taking maintenance 4.0 elements into account. Therefore, the potential benefits of maintenance 4.0 from the safety perspective is revealed.

Since the HRA of marine engineering literature is not fruitful, more effort is required to this domain. All of the mentioned studies are not quantified marine engineering specific EPCs based on a meticulous research. The study of Islam et al. (2017) stands as the most significant attempt which aims to quantify marine engineering specific EPCs. This study also includes the marine maintenance operations however; their EPC findings are not based on the actual ship data. Instead, they are benefitted from expert judgments to create marine engineering specific EPCs. Despite their valuable contribution to the literature, more reliable, more sensitive and actual data based HRA approach is required for marine engineering field. Moreover, applications of HRA based studies towards ship maintenance and other engine room specific operations should be enrichened through various case studies. Domain specific approaches, various applications along with their valuable findings can remedy these gaps significantly in marine engineering and HRA literatures.

3. METHODOLOGY

The methodology of this research is explained under relevant sections, comprehensively. At first, currently known approaches which are utilized to method development are introduced. Following, the MMOHRA technique is proposed with modified HFACS-MMO. Finally, methodological improvement of the proposed MMOHRA is given through a rule based practical calculation tool.

3.1 Methodological Background

The proposed methodology consists of different techniques such as SOHRA, HFACS, AHP and T-Test. These techniques are introduced in the next sections.

3.1.1 The SOHRA method

In this section, the steps of SOHRA are introduced in details. As seen in the equation (3.1), the generic errors probability (GEP), EPC and assessed proportion effect (APOA) are required to calculate HEP values. If there is more than one EPC, then APOA can be implemented to specify the proportion effect of each EPC.

$$HEP = GEP \times \left\{ \prod_{i} \left[(EPC_i - 1) APOA_{pi} + 1 \right] \right\} \tag{3.1}$$

The EPC values indicate the weight of an EPC, thus where the EPC value is high, the likelihood of error is greatly increased by the defined condition. The complete list of 38 EPCs are shown in Table 3.1, with their maximum affect values. Generic task type (GTT) is another required parameter for HEP calculations in SOHRA. The descriptions of GTT and the nominal human unreliability values of each (GEP) are not different in HEART based HRA methods, such as SOHRA.

Table 3.1 : EPC values of SOHRA (Akyuz et al, 2016).

Code	Error producing condition	Maximum affect
EPC1	Unfamiliarity	17.00
EPC2	Time shortage	14.01
EPC3	Low signal-noise ratio	3.31
EPC4	Features over-ride allowed	8.72
EPC5	Spatial and functional incompatibility	5.76
EPC6	Model mismatch	2.64
EPC7	Irreversibility	2.23
EPC8	Channel overload	14.45
EPC9	Technique unlearning	5.29
EPC10	Knowledge transfer	11.00
EPC11	Performance ambiguity	8.60
EPC12	Misperception of risk	12.51
EPC13	Poor feedback	12.55
EPC14	Delayed/incomplete feedback	6.72
EPC15	Operator inexperience	10.03
EPC16	Impoverished information	8.42
EPC17	Inadequate checking	2.79
EPC18	Objectives conflict	2.15
EPC19	No diversity	2.74
EPC20	Educational mismatch	2.88
EPC21	Dangerous incentives	3.62
EPC22	Lack of exercise	1.64
EPC23	Unreliable instruments	5.69
EPC24	Absolute judgements required	1.17
EPC25	Unclear allocation of function	1.22
EPC26	Lack of progress tracking	3.28
EPC27	Physical capabilities	4.35
EPC28	Low meaning perception of unimportance	2.56
EPC29	Emotional stress	1.59
EPC30	ill-health	0.89
EPC31	Low morale	3.00
EPC32	Inconsistency of displays	9.43
EPC33	Poor environment	9.90
EPC34	Low mental workload	2.63
EPC35	Sleep cycles disruption	10.30
EPC36	Task pacing	3.85
EPC37	Supernumeraries	4.14
EPC38	Age	3.61

Hence, GTT depicts the class of a task in accordance with the the task related definitions. Once the GTT of each subtask is specified, GEP values can be assigned correspondingly. GTT definitions and GEP values are listed in Table 3.2. According to the SOHRA, the following steps should be taken in order to calculate the HEP of a maintenance practice.

Table 3.2 : GTT definitions and GEP values (Akyuz et al, 2016; Williams, 1998).

GTT		Nominal Human Unreliability (GEP) (5th -95th percentile Bounds)
A	Totally unfamiliar; performed at speed with no real idea of likely consequences	0.55 (0.35 - 0.97)
B	Shift or restore system to a new or original state on a single attempt without supervision or procedures	0.26 (0.14 – 0.42)
C	Complex task requiring high level of comprehension and skill	0.16 (0.12 – 0.28)
D	Fairly simple task performed rapidly or given scant attention	0.09 (0.06 – 0.13)
E	Routine, highly practiced, rapid task involving relatively low level of skill	0.02 (0.07 – 0.045)
F	Restore or shift a system to original or new state following procedures with some checking.	0.003 (0.0008 – 0.007)
G	Completely familiar, well-designed, highly practiced, routine task occurring several times per day, performed to highest possible standards by highly motivated, highly trained, and experienced personnel, with time to correct potential error, but without the benefit of significant job aid.	0.0004 (0.00008 – 0.009)
H	Respond correctly to system command even when there is an augment or automated supervisory system providing accurate interpretation of system state	0.00002 (0.000006 – 0.0009)
M	Miscellaneous task for which no description can be found	0.03 (0.008 – 0.11)

Step 1. **Task Analysis**: A hierarchical task analysis is performed to evaluate the main tasks and their sub-tasks. So, EPCs and GEPs can be assigned for each subtask to reach more precise HEP values.

Step 2. Operating Conditions: In this step, operating conditions for selected maintenance tasks are defined so that the definitions of GTT and EPC can be easily matched to specified subtasks. Different scenarios may involve various factors, such as exhaustion, overloading, crew experience, and lack of familiarity, according to the specific conditions.

Step 3. GTT and EPC assignment: For a maintenance process, GTTs and EPCs should be chosen by the responsible experts, properly. For a subtask, more than one

EPC can be allocated. In this sitiuation, the weights of each EPC for a specific sub-task can be collected via APOA calculation.

Step 4. APOA calculation: This calculation is executed in attempt to identify the proportional effect of each selected EPC. In the SOHRA, this process takes advantage of the AHP as a MCDM tool to have more precise results.

Step 5. HEP calculation: Once the APOA calculation process is performed, HEP values can be calculated as equation (3.1) indicates. In this equation, EPC_i is the i^{th} (i= 1,2,3,......n; n $\leq$ 38) EPC and $APOA_{pi}$ ($0 < pi \leq 1$) is i^{th} the assessed of proportion affect; as it is explained in Step 4.

3.1.2 The HFACS method

This method substantially developed upon the Swiss cheese model, which is intended by Reason (1990). In the Swiss cheese approach, weak points of organizations that leads failure are represented as holes for each level of human factors on a Swiss cheese. Further, as a comprehensive approach; the HFACS has been proposed for accident analysis in the aviation sector by Shappel and Wiegmann (2000). Since HFACS classifies human factors adequately, it allows researchers to recognize safety vulnerabilities considering active and latent causes that may contribute to accidents.

The HFACS classifies human factors as i) unsafe acts of operators, ii) preconditions for unsafe acts, iii) unsafe supervision, iv) organisational influences. The framework of the conventional HFACS is shown in Figure 3.1. Until today, the HFACS utilized in different domains such as mining (Lenne et al, 2012; Liu et al, 2018), railway (Zhan et al, 2017), chemistry (Gong and Fan, 2016; Zhou et al, 2019), oil & gas industry (Theophilus et al, 2017), road traffic (Patterson and Shappell, 2010) and marine (Chauvin et al, 2013; Akyuz and Celik, 2014; Soner et al, 2015). Utilization of HFACS in maritime accident analysis generally developed upon the accident types such as collision, grounding, fire and explosion. For instance, Chauvin et al, (2013) examined 27 ship accidents which consist of “collisions” between 1998 and 2012. They have also made some modifications over HFACS and they annexed “outside factors” for the collision based ship accidents in order to conduct more accurate classification.

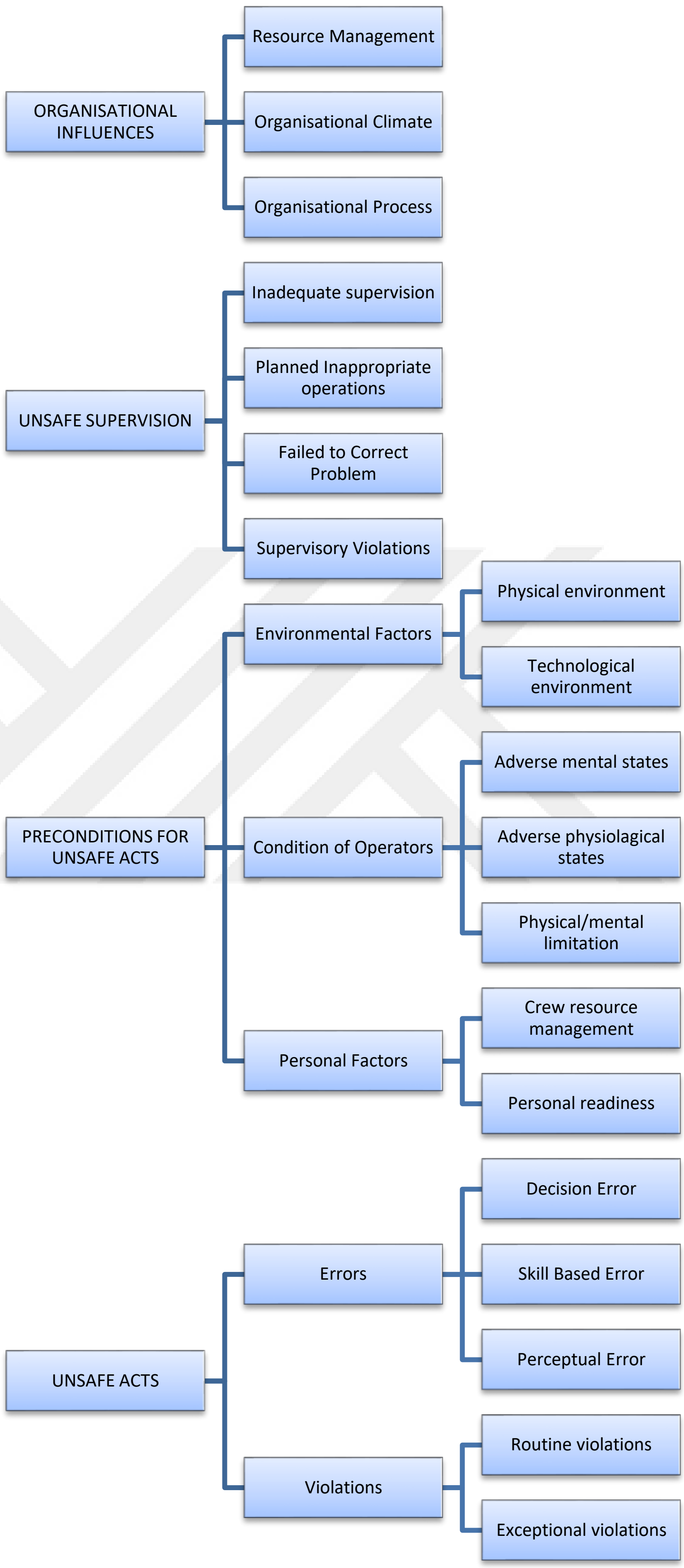

Figure 3.1 : The HFACS framework (Shappel and Wiegmann, 2000).

3.1.3 The AHP Method

The AHP is a multi-criteria decision making tool developed to determine relative importance weights of given criteria in complex decision making problems (Saaty, 1980). The AHP offers a pair-wise comparison between the alternatives in order to simplify decision making process.

Table 3.3 : Saaty's linguistic pair-wise scale.

Importance	Description
1	Equal importance
3	Moderate importance of one over another
5	Strong or essential importance
7	Very strong or demonstrated importance
9	Extreme importance
2,4,6,8	Intermediate values

In this study, Saaty (1977)'s pairwise comparison scale is utilized, as it is shown in Table 3.3. The AHP consists of three phases as explained below:

I) Composing a pair-wise comparison matrix: In this phase, the relative weight of each element is revealed through a pairwise comparison matrix using Saaty's 1-9 linguistic scale (Saaty, 1986). Let a matrix be A, and the total amount of evaluated alternatives is n, numerical code of each alternative is a_{ij} $(i,j = 1,2,3,...,n)$. a_{ij} nominations are inserted in the matrix with A which representing the relative importance of the i^{th} against to the j^{th}. See equation (3.2). In SOHRA, if i^{th} EPC is more important than j^{th}, then $a_{ij} > 1$, or vice versa. See equation (3.3).

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & 1 \end{bmatrix} a_{ii} = 1,\ a_{ji} = 1/a_{ij},\ a_{ij} \neq 0 \qquad (3.2)$$

$$a_{ij} \times a_{ji} = 1 \qquad (3.3)$$

II. Calculating criteria weights: Criteria weights are calculated in accordance with the pairwise Matrix A for each alternative. See equation (3.4).

$$w_i = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \tag{3.4}$$

III. Checking consistency rate: Ultimately, a consistency analysis is carried out to evaluate the reliability of pair-wise comparison matrix data. The consistency rate (CR) in AHP is calculated as equations (3.5-3.7), respectively (Saaty, 1980).

$$CI = \frac{\lambda_{max.} - n}{n-1} \tag{3.5}$$

$$\sum_{j=1}^{n} \alpha_{ij}\, w_j = \lambda_{max}\, w_i \tag{3.6}$$

$$CR = CI/RI \tag{3.7}$$

If the CR values are obtained to be equal or less than 0.10, the expert judgements which are inserted in the comparison matrix are considered consistent. In case of inconsistency, the experts should review their judgments.

Table 3.4 : The RI values (Saaty, 1980).

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

In the equation (3.7), CI and RI refers consistency index and random index respectively. The RI values can be obtained from the Table 3.4. In these equations, n indicates the order of matrix and λ_{max} denotes the maximum matrix eigenvalue.

3.1.4 The independent t-test

The independent t-test is a statistical method that compares the mean values of two different groups (Ruxton, 2006). The t-test is performed to determine if there is a substantial difference between the two-group tests. The equation (3.8-3.10) are given for the measurement of a t-test.

$$t = \frac{\overline{Y_1} - \bar{Y}_2}{S_p\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}} \tag{3.8}$$

$$S_p = \sqrt{\frac{(n_1-1)S_1^2+(n_2-1)S_2^2}{n_1+n_2-2}} \tag{3.9}$$

$$d_f = n_1 + n_2 - 2 \tag{3.10}$$

In these equations, the notations are; t= t-test, $\overline{Y_i}$=mean of i. sample, n_i=mean of i. sample size, S_p=Pooled standard deviation, S_1andS_2= Standard deviation of S_1 and S_2, respectively, d_f= degree of freedom.

3.2 Methodology Improvement

Since the aim of the study is to establish an effective, comprehensive marine engineering specific human error calculation approach in order to enhance operational safety on ship auxilliary machinery operations; specific EPC values for Marine Maintenance and Operations Human Reliability Assessment (MMOHRA) should be found. The proposal of MMOHRA has two significant objectives. The first one is modification of the initial HFACS into HFACS-MMO. The reason of this is to new classification requirements of engine room based accident causes. The second is determining marine maintenance and operations specific mmo-EPC values. Since EPCs are the most decisive parameters in the calculations of human reliability analysis techniques, mmo-EPCs should be determined sensitively in order to conduct more accurate predictions in marine engineering operations. The mmo-EPC derivation framework is shown in Figure 3.2.

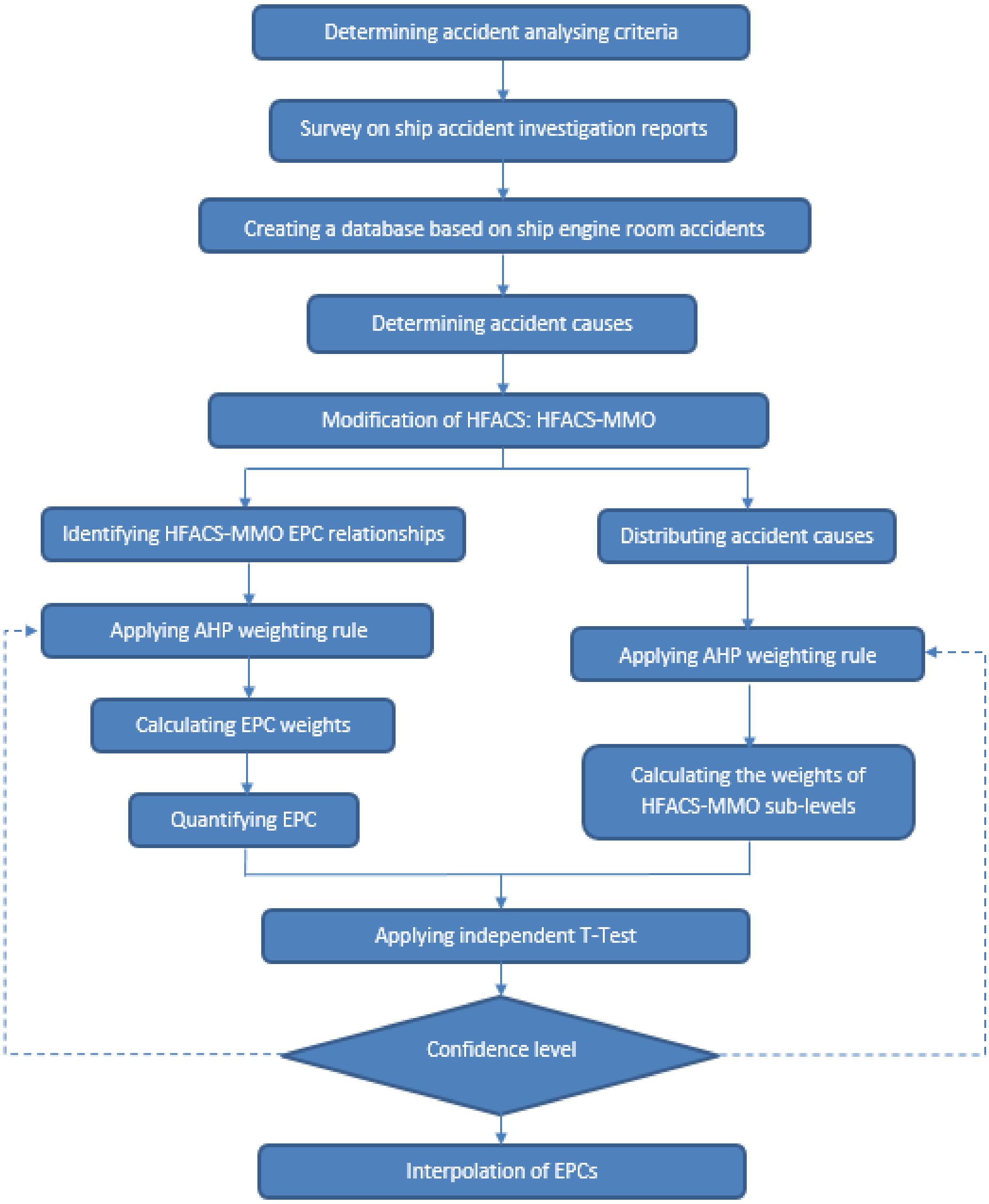

Figure 3.2 : The mmo-EPC derivation framework of MMOHRA.

3.2.1 HFACS-MMO framework

In this section, marine engineering specific HFACS is proposed. This approach is a modified version of the conventional HFACS. Firstly, a brief review of selected reports is introduced. Later, a causation analysis is explained to highlight relationships between accidents and their causes. Finally, weightings of each HFACS-MMO levels are determined via proper distribution, classification and calculation of the causes.

3.2.1.1 Review of selected reports

Since the paper's objective is to identify marine engineering specific EPCs, the initial step is to review ship accident investigation reports to discover whether or not the causes originated by the engine room crew. In addition, since the derived EPCs should be reliable for future efforts to forecast human reliability, the historical data should be recent as possible. Consequently, the accidents that happened before 2008 are not considered as credible data and are not included in this analysis.

Table 3.5 : Distribution of accident investigation reports.

Quantity	Short Name	The Name of the Organizations	Center
1	AIBN	The Accident Investigation Board Norway	Norway
16	ATSB	Australian Transport Safety Bureau	Australia
3	BSU	Federal Bureau of Maritime Casualty Investigation	Germany
1	JTSB	Japan Transport Safety Board	Japan
15	MAIB	Marine Accident Investigation Branch	UK
13	MSIU	Marine Safety Investigation Unit	Malta
7	NTSB	National Transportation Safety Board	USA
3	SMAIC	State Marine Accident Investigation Commission	Poland
1	TAIIB	Transport Accident and Incident Investigation Bureau Investigation Bureau	Latvia
4	TSB	Transportation Safety Board of Canada	Canada
2	USCG	United States Coast Guard	USA
4	BMA	Bahamas Maritime Authority	Bahamas
70	**Total**		

Besides, documents of the accident investigation containing incomplete or missing incident information are also not taken into account during the creation of the database. According to these requirements, a quantity of 1380 ship accident reports is investigated and only 70 of them are selected to the database. Eventually, distribution of the accident investigation reports which are selected for this study is shown in Table 3.5. Since the causes of accidents, course of events, responsible staff, organizational deficiencies show variety, causation analysis is required to grasp the basic dynamics of this subject clearly.

3.2.1.2 Causation analysis

In terms of direct or indirect causes, accidents may involve various types of safety concerns when leading to failures. Besides, a number of defects may be found that can impede emergency recovery efforts during or just before the accidents. For this reason, prior to the HFACS classification; the causes of accidents should be distinguished according to their impact on the accidents. Hence, causation forms in the investigation reports are analysed in 4 different groups and their relative weights are identified by AHP. Thereby, the assigned weights of cause types are shown in Table 3.6.

Table 3.6 : Importance weights of cause types.

Cause Types	Definition	Weights
A	Safety issues which have major impact lead to the accident	0.48
B	Safety issues which have moderate impact lead to the accident	0.23
C	Safety issues which have low impact to the accident	0.13
D	Safety issues which hinder emergency actions	0.16

According to the accident investigation reports, a ship accident often has more than one cause. In this study, a total of 435 marine engineering accident causes are derived from the 70 investigation reports. An example of the cause distribution of *Carnival Triumph accident (2013)* resulted by a "fire in the engine room" is shown in Table 3.7. As shown in the table, the essential safety problems in relation to the improper replacement of fuel pipe are caused an oil leakage. In this accident, investigators claimed that there is no recording has been found for fuel pipe replacement operation, as well as there is no common maintenance schedule for the inspections. These violations lead the oil leakage which caused a fire when it contacted with the hot surfaces in the engine room. In addition, some emergency equipment's poorly maintained or inadequate situation in combination with a lack of fire training makes fire spread out of control.

At the other hand, some of the current definitions about maintenance and operations in marine engineering should be specialized. In this context, the HFACS studies in the maritime literature such as Chen et al. (2013), Soner et al. (2015), Chauvin et al. (2013), and Uğurlu et al. (2018) are carefully investigated on the purpose of suggesting HFACS-MMO more accurately. In details, considering the circumstances of maritime organizations, the causes resulting from the external factors are very typical in terms of "*Inappropriate shore services*", "*Manufacturer deficiencies*" and "*Inadequate design of the engine room*".

Table 3.7 : Classification of accident causes for a particular vessel.

Causes	A	B	C	D	HFACS-MMO Code
The electrical system was vulnerable for total loss of power			X		4b
The oil leakage was visible and have not been identified by the crew	X				3c
There was no record of the fuel pipe delivered aboard, no inventory, no certificate also.	X				2b
The Fuel oil system had no quick closing valves in the fuel oil system				X	2d
There was no common maintenance schedule for engine room inspections of oilers		X			2c
Ship's PMS should have included emergency generator inspections		X			2c
Maintenance of some emergency equipment have not been conducted properly				X	5d
Lack of fire drill in the engine room				X	3d

According to the selected accident investigation reports, the "external factors" can be a serious safety issue that leads to an accident. There have been errors made by the shore services, manufacturer deficiencies and inadequate design of the engine room. Since these aspects are not originated from the engine room, they can be considered as *"external factors"* in HFACS-MMO structure. For instance, "poor air cooler design by the manufacturer (Carnival Splendor Passenger Ship)", "maintenance instructions did not provide sufficient guidance by the manufacturer (Qian Chi Oil Tanker)", "the port did not respond effectively for external fire fighting support (Marigold Bulk Carrier)", "system design does not permit draining procedure for the equipment (Ocean Ranger Bulk Carrier)" are causes that contributing to this type of safety issues.

The second layer of HFACS is "*organizational factors*". This group of factors are mostly matched with the marine maintenance operations however; descriptions have been reviewed in order to clarify the relevant aspects. "*Resource management*" sub-layer refers the organization's influence on adequency level of equipment and tools, condition of spare parts, investing level towards safety equipment and trainings for the personnel working in the engine room. To exemplify; "the overalls and other protective equipment did not provide adequate protection against hot condensate and steam (Celebrity Constellation Passenger Ship)", "no spare flexible hoses of the type used on the fuel gauge were available on board (Balkan Container Ship)", "the company did not provide training course for the engine (Delfini Passenger Ship)". The "*organisational climate*" sub-layer deals with deficiencies and inconsistencies in the organizational structure, policies and culture that influence the performance of engine room crew. Typical errors of this class are: "none of the crew attempted to analyse the situation (Norfolk Express Container Ship)", "risk of the main engine failing due to unresolved problems surrounding the supply of lubricating oil which was obvious and not identified (Conmar Avenue Container Ship)", "on several occasions, conversations between crew members were conducted in Tagalog language (Grand Rodosi Bulk Carrier)". Another sub-layer is "*organisational process*" which indicates the deficiencies related to organisational management such as rules, manuals, guidances, standards, work/rest hours, time pressure, encouragement, shift orders, risk analysis, risk management, etc. The most common safety issues for this sub-layer are: "there were lack of adequate procedures and instructions onboard the ship (Poprad Cargo Ship)", "ship's SMS had multiple deficiencies (Moondance Ro-Ro Ship)", "original system drawings were not clear (Pride of Canterburry Ro-Ro Ship)", "instruction books contribute the crew's lack of awareness due to deficient descriptions (Alliance St Louis Ro-Ro Ship). In addition to these sub-layers, a sub-layer has been attached to this layer as "emergency procedures". Since the emergency procedures are very critical actions on-board a ship, they must strictly carry out. Despite the fact that these procedures are subjected to the strict international maritime rules, the implementation phase is dependent on the organizational influences as well as supervisory actions. According to the records, a vast majority of emergency procedure violation types are arisen from organisational influences such as; "Safety shoes had ineffective insulation protection (Logos Hope Passenger Ship)", "High pressure alarm does not exist for early accident detection (Pride of Canterbury Ro-Ro Ship)", "The alarm system was violating international maritime rules of SOLAS, LSA (Amaranth Cargo Ship)", "Halon gas fixed fire suppression system was not consistent with proper maintenance & testing (Marigold Bulk Carrier)".

"*Unsafe supervision*" layer is another important human factor class in the original HFACS. This type of errors is well-matched with the marine maintenance and operations however; their descriptions have been reviewed. For emergency situations, lack of drill based deficiencies were examined in this categorization, under the sub-layer of "*inadequate supervision*". This sub-layer deals with hazard identification, controlling the risks at the supervisory level such as “Compressor was not inspected to ensure operating satisfactorily (River Embey Bulk Carrier)”, “Lack of testing for bilge systems (Tall Ship Bounty Special Ship)”, “Leakage alarms have not been inspected or maintained (Thompson Majesty Passenger Ship)”. *“Inadequate supervision”* and *“Planned Inappropriate Operation”* can also be seen at moderate level. In this type of error, unnecessarily made hazardous attempts decided to be done by the supervisors are come into prominence. The examples of the related causes are; “There was no risk assessment conducted for diesel generator thermometer change (Pine Galaxy Chemical Tanker)”, “There was no operator assigned for the maintenance procedure (Delfini Passenger Ship)”, “Salvage pump was defective and it was not subjected to regular maintenance (Amy Harris Tug Ship)”. In *“supervisory violations”,* the deficiencies have arisen from the disregard of supervisors towards international rules, ship’s SMS, standards and certain procedures. To exemplify; “Chief engineer's standing orders was ineffective and violating the rules (Arco Avon Tug Ship)”, “The system had not been rectified in accordance with the company's procedures and other international requirements (Azamara Quest Passenger Ship)”, “Ship’s critical equipment and systems were not tested and maintained in accordance with the ISM Code (Clonlee Cargo Ship)”. The *“failure to correct known problem”* deals with the failures of supervisors towards known problems such as corrective actions for a deficiency on equipment, procedure, process, guidance, documentary, etc. The examples for typical causes are: “The auxiliary engine fuel supply pipework was unsupported, which led to oil leakage (Amy Harris Tug Ship)”, “There was lack of simple prevention to mitigate the risks (Skysea Golden Era Passenger Ship)”, “There was dangerous electrical current in the protective system (Moondance Ro-Ro Ship)”.

The descriptions and separation system of “*preconditions*” layer has changed and specialized for the engine room crew. Therefore, sub-layers of this group are: i) *Condition of Engineer*, ii) *Engine Room Physical Environment*, iii) *Engine Room Technological Environment*, and iv) *Engine Room Crew Management*. For “*condition of engineer*”; “deviations were not observed before the incident due to complacency (Qian Chi Oil Tanker)”, some of the crew had improper sleep cycle (American Dynasty Tug Ship)”, “there was not sufficient time to make emergency corrections (Hebrides Ro-Ro Ship) are typical causes whilst for “*engine room physical environment*”; “the flexible hose fitted to the gauge was not physically visible (Balkan Container Ship) , “the main engine was fitted with a scavenge air space collector improperly (Ocean Ranger Bulk Carrier), "weathertight doors were not closing (Denarius Tug Ship)", for "*engine room technological environment*"; "back pressure pump wear was not detected in oil sampling programme (Pride of Canterburry Ro-Ro Ship)", "the crew were unfamilliar to the system (Key Bora Chemical Tanker) and finally for "engine room crew management"; "poor communication between senior officers (Great Majesty Bulk Carrier), "when blackouted, lack of coordination & situational awareness were shown by the crew (Clonlee Cargo Ship)", "unclear and time consuming responsibilities were given to officers (Conger Oil Tanker)".

The layer of "*unsafe acts*" is the last cathegory for HFACS: the fourth for conventional HFACS, the fifth for HFACS-MMO. Apart from the descriptions and special identifications, this layer remains very similar with the original HFACS.

The "*skill based errors*" sub-layer has typical safety issues such as "malfunction detection was failed despite the alarm sound (River Embley Bulk Carrier)", "in another maintenance operation, nozzly assembled incorrectly (Qian Chi Oil Tanker)", "the operator has made a wrong assumption (Seven Seas Voyager Passenger Ship)", "oil drained improperly while loosening the boiler fuel connections (Saldanha Bulk Carrier)". The second sub-layer is "*rule based mistakes*". The typical safety issues are: "technical emergency situation check cards were not used (Pride of Calais Ro-Ro Ship)", "the O-ring was not replaced during the last maintenance operation (Thomson Majesty Passenger Ship)", "emergency CO2 released too early by the crew (Patrice McAllister Tug Ship)." The "*knowledge based mistakes*" has common causes such as: "the ship operator decided to continue with passenger voyages using a single propulsion unit (Norwegian Star Passenger Ship)", "the crew chose a wrong gasket and mounting it on the output flange of the adapter of the pump (Amaranth Cargo Ship)", "the engineer has lack of knowledge about which fuse is proper for the situation (Poprad Cargo Ship)". The "*routine violations*" usually arisen from the procedural mistakes which address the everyday tasks, or the violations which become chronicle among the engine room crew. The examples for this type of errors are; "maintenance procedures have not been followed (Carnival Splendor Passenger Ship)", "the crew did not present their report for the diesel oil smell (Ken MacKenzie Tug Ship)", "engine room checklists were used poorly (Moondance Ro-Ro Ship)", "the crew had been manually controlling the jacket water temperature during engine load changes (FR8 Pride Oil Tanker)".

Table 3.8 : HFACS-MMO classification system.

Code	HFACS-MMO levels	Safety Issues
1	**External Factors**	
1a	Inappropriate Shore Services	• Service engineer or technician based errors • Poor emergency response of port management • Port authority or classification society based deficiencies
1b	Manufacturer Deficiencies	• Absent or deficient maintenance manuals of the manufacturer • Poor equipment design • Discrepancy between maintenance instructions and operational manuals
1c	Inadequate Design of ER	• Poor engine room design which does not allow to make safe inspections • Poor arrangement of engine room systems • Incorrect equipment instalments
2	**Organisational Factors**	
2a	Resource Management	• Poor or lack of training of the crew • Lack of machinery spare parts, safety equipment or alarm systems • High numbers of inexperienced or unfamiliar engineering officers assignment in a short term
2b	Organisational Climate	• Engine room crew desensitized to a specific repetitive failure or false alarms as a result of poor safety culture. • Safety precautions often not by-passed by the crew • Incoordination between deck and engine room crew towards safety actions
2c	Organisational Process	• Technical information provided by the company does not provide sufficient detail about maintenance & operation of equipment • Ship's PMS has deficiencies or did not require testing for critical equipment including alarms, new devices. • No guidance is provided for defect reporting of the vessel
2d	Emergency Procedures	• Poor emergency strategy development or poor internal audit by the company. • Absent or inadequate instalment of critical emergency response systems such as the quick closing valves for the main engine, or other emergency stop buttons • Several deficiencies on emergency response systems including alarm systems
3	**Unsafe Supervision**	
3a	Inadequate Supervision	• Inadequate guidance from chief engineer • Inadequate inspections which should be conducted before the starting or restarting the machinery or equipment • Lack of drills onboard.
3b	Planned inappropriate operation	• Lack of risk assessment is conducted for the engine room operations by a supervisor. • Supervisor orders by-passing the hot work permit procedure • Inexperienced crewmember assignment for critical maintenance or operational tasks
3c	Failure to Correct Known Problem	• The acknowledgement of a specific problem such as unsupported auxiliary engine fuel supply pipework, which leads to oil leakage. • Poor insulation or covering of equipment which may lead to potential hazards. • No permanent solution attempt is made towards identified failures

Table 3.8 (continued) : HFACS-MMO classification system.

3e	Supervisory Violations	• Intended violation of rules by standing orders of Chief engineer • Improper guidance provided by the supervisor engineer. • A specific risk assessment for a task is not carried out despite the existing company instructions
4	**Preconditions**	
4a	Condition of Operator	• Overconfidence to the specific system or equipment by the engine room crew • Being too reliant upon checklists despite the needs for additional actions • System parameters are not monitored due to complacency
4b	ER Physical Environment	• Poor lighting in the engine room which makes difficult to carry out some tasks. • Heavy weather which causes fatigue or irregular sleep order on the crew
4c	ER Technological Environment	• Broken system monitoring devices which disallow to monitor some parameters • Problems on electronic PMS system • The complexity of controller systems such as pitch controller system
4d	ER Crew Management	• Poor communication and/or interaction between engine room crewmembers • Poor situational awareness towards executed operations • Poor recording to the log-books
5	**Unsafe Acts**	
5a	Skill Based Error	• Malfunction detection failures by the crew in critical situations. • Unrevealed mechanical failure during the routine maintenance • Unintended but inadequate maintenance of engine room equipment or machinery.
5b	Rule Based Mistakes	• Ignoring the existing instructions • Carrying out an operation by improper and hazardous methods • Use of improper tool for an engine room operation
5c	Knowledge Based Mistakes	• The persistence of the same problem despite conducting maintenance or repair of an equipment • Unsuccessful troubleshooting efforts towards a malfunction. • The crew can not complete a maintenance operation or overhauling which creates pressure among them.
5d	Routine Violations	• Rules and instructions frequently not followed by the crew • Some inspections are conducted shortly or not conducted for a long time. • Required log-book or parameter controls are not made accordingly by the crew
5e	Exceptional Violations	• The engineer or officer on watch violates the ship's SMS due to time shortage • The risks of injury are perceived as acceptable or acknowledged despite the existing safety rules • The machinery or equipment is not maintained in accordance with the requirements of the regulations

The “*exceptional violations*” indicate the rarely made human errors in some circumstances in attempt to finish a work as soon as possible to get rid of it. This type of errors usually violates the international maritime rules due to focusing on “completing the task” instead of the “task” itself. Some examples are: “there was a violation to the ship's SMS (Saffier Cargo Ship)”, “the 3rd engineer did not wear safety equipment (Arco Avon Tug Ship)”, “necessary tests have not been conducted by the crew (Rost Ro-Ro Ship)”, “the crew have uncovered all the shielding guards while the main engine running (Usichem Oil Tanker)” and “incorrect welding causes fail for the coil of oil heater (Dieppe Seaways Ro-Ro Ship)”.

Ultimately, the HFACS-MMO system can also be defined as in Table 3.8. In this table, descriptions and their classification levels in accordance with the safety issues are listed.

3.2.1.3 Weightings of HFACS-MMO levels

Weightings of each HFACS-MMO levels can be calculated via proper distribution of all causes into sub-levels. In this calculation, the classification based values of causes (A, B, C or D) which indicate their significancy leading to the accident is also taken into account.

When the HFACS-MMO levels are established, the 435 causes are distributed accordingly as shown in Figure 3.3. The frequencies of the causes are also indicated in this calculation. Additionally, the color classes indicate the same upper-level groups of HFACS-MMO.In parallel to the HFACS-MMO, all causes are classified in accordance with their impact types (A, B, C or D). Later, the weights of each HFACS-MMO sub-levels are calculated with the multiplying of the cause quantities with the values of their impact types. The weights obtained for each sub-level are shown in Table 3.9. These values are also important for this study's mmo-EPC derivation process which is explained in the next section.

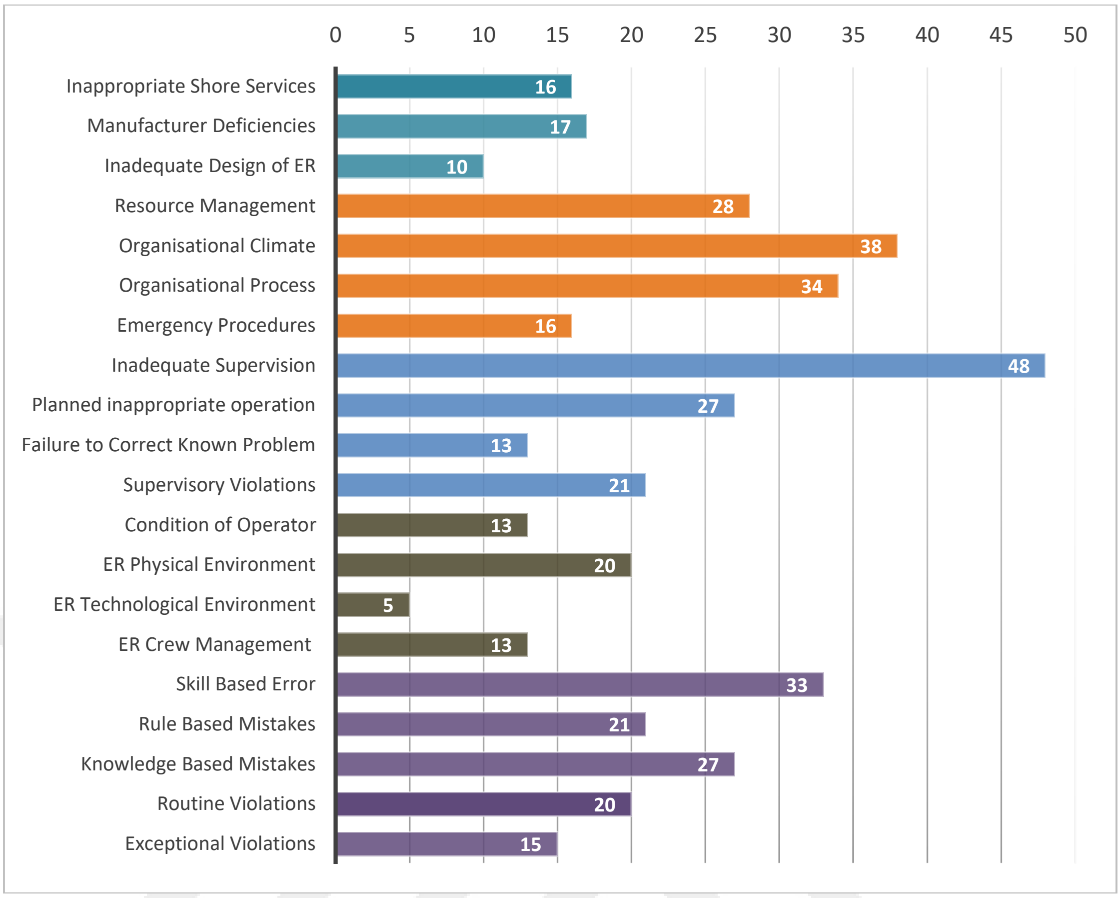

Figure 3.3 : Distribution of all causes to HFACS-MMO.

In this table, the HFACS-MMO levels can also be reflected as their percentage values, without taking their impact types (A, B, C, D). The "*external factors*" corresponding 10% of all causes, approximately. The layer of "*organisational factors*" have 26.7%, "*unsafe supervision*" based safety issues consist 15%, the "*preconditions*" has 11.7%, and "*unsafe acts*" have 26.7% of all accident causes, the highest value along with the "*organisational factors*".

Table 3.9 : The weights of HFACS-MMO levels.

	HFACS-MMO Levels	A	B	C	D	Weights	Total
1	**External Factors**						
1a	Inappropriate Shore Services	11	2	1	2	6.07	
1b	Manufacturer Deficiencies	14	3	0	0	7.61	
1c	Inadequate Design of ER	4	5	0	1	3.22	
							16.9
2	**Organisational Factors**						
2a	Resource Management	11	13	0	4	8.40	
2b	Organisational Climate	15	13	10	0	11.64	
2c	Organisational Process	23	7	2	2	13.13	
2d	Emergency Procedures	3	3	1	9	2.42	
							35.59
3	**Unsafe Supervision**						
3a	Inadequate Supervision	18	6	3	21	10.61	
3b	Planned inappropriate operation	18	6	1	2	10.35	
3c	Failure to Correct Known Problem	4	4	3	2	3.39	
3d	Supervisory Violations	12	5	2	2	7.35	
							31.70
4	**Preconditions**						
4a	Condition of Operator	4	7	2	0	3.93	
4b	ER Physical Environment	4	7	7	2	4.58	
4c	ER Technological Environment	3	2	0	0	2.06	
4d	ER Crew Management	4	2	6	1	3.33	
							13.90
5	**Unsafe Acts**						
5a	Skill Based Error	24	8	0	1	13.58	
5b	Rule Based Mistakes	16	3	0	2	8.58	
5c	Knowledge Based Mistakes	19	6	1	1	10.84	
5d	Routine Violations	15	2	2	1	8.14	
5e	Exceptional Violations	9	3	0	3	5.19	
							46.33

3.2.2 EPC Values of MMOHRA

This section explains derivation of mmo-EPCs. A relationship matrix between HFACS-MMO and EPCs is necessary for this process. Although Williams (1988) provides a clear description of each EPC in the original HEART, maintenance and operations in marine engineering require a redefinition. At this stage, in addition to the existing knowledge gathered from accident analysis, certain papers such as Kim and Yung, (2003), DiMattia et al. (2005), Noorozi et al. (2014), Islam et al. (2017) are carefully examined. Ultimately, the updated definitions of EPCs are described in Table 3.10 specifically for maintenance and operations in marine engineering. The mmo-

Table 3.10 : Descriptions of mmo-EPCs.

EPCs	Descriptions for marine engineering maintenance & operations
EPC1	Lack of familiarity with the engine room systems which occurs infrequently during operation/maintenance tasks
EPC2	A shortage of time available for error detection and correction in the engine room
EPC3	The low signal-noise ratio due to noise in the engine room
EPC4	Inadequate technical manuals, instructions or software for specific machinery/equipment which contains suppressing or overriding information
EPC5	No means of useful information for a specific equipment in a form of technical manuals or software tools
EPC6	An incompatibility between engine room operator's practice and that of the engine room designer
EPC7	No obvious means of reversing an unintended engine room operation
EPC8	An overload of non-redundant information or data for an operational task
EPC9	A need to approach to an engine room operation with opposing philosophy
EPC10	The need to transfer specific knowledge from task to task without loss
EPC11	Ambiguity in the required performance standard which regulated by IMO rules or ship management system
EPC12	A mismatch between the perceived and real risk of the marine engineering operations
EPC13	Poor, ambiguous or ill-matched engine room log book recordings which have been written by another crew
EPC14	No clear direct and timely confirmation of an intended action from a system in the engine room
EPC15	The engineer inexperienced, newly qualified or newly assigned onboard
EPC16	Poor quality of information conveyed between engine room crew
EPC17	Little or no inspection & test conducted for specific equipment/machinery by the supervisor
EPC18	A conflict between immediate and long term objectives of the engine room tasks
EPC19	Insufficient data variety for veracity checks of systems
EPC20	A mismatch between the educational achievement level of the engineer and the requirements of the task
EPC21	Supervisor guidance leads to use of other more dangerous or improper procedures
EPC22	Lack of opportunity to exercise mind and body outside the engine room
EPC23	Inadequate or insufficient equipment, tools and spare parts for the engine room
EPC24	A need for absolute judgments which are beyond the engineer’s capabilities
EPC25	Poor responsibility distribution among engine room crew
EPC26	No obvious way to keep monitor of progress during an engine room operation
EPC27	A danger which exceeds finite physical capabilities of the engineer
EPC28	Little or no importance is given to the maintenance or operational task
EPC29	High level of the emotional stress of the engineer due to long term working at sea, homesick or lack of adaptation
EPC30	Evidence of ill health of the responsible engine room crew
EPC31	Low workforce morale of engine room crew
EPC32	Inconsistent guidance, drawings or procedures for a specific task
EPC33	Poor, hostile and uncomfortable condition of the engine room
EPC34	Prolonged inactivity or highly repetitious cycling of low mental workload of the engineer
EPC35	The irregular work sleep cycle of the engine room crew
EPC36	Standard task process intervened by the involvement of other seafarers in the engine room
EPC37	Higher or fewer numbers of engineers/operators than required for a specific task
EPC38	The operator's age and physical capabilities not proper perceptually for specific marine engineering maintenance or operations.

EPC and HFACS-MMO relationship matrix can be built by distributing the EPCs to appropriate HFACS-MMO sub-levels. The study of Akyuz et al. (2016) is taken into consideration for this process. Finally, the established matrix is provided in Table A.1 in the Appendices section. Since there are a number of relationships in the matrix, the degree of significance of each EPC should be defined along with the related sub-levels of HFACS-MMO.For this purpose, the AHP approach was implemented as a MCDM tool. For instance, the assigned weights for the *inappropriate shore services* are in connection with the EPC2, EPC7, EPC18 and EPC24. After establishing the pairwise matrices of these EPCs, the assigned weights are identified via multiplying the weighting of *inappropriate shore services* (See: Table 3.9, the value of 6.07). These contributory values of EPC2, EPC7, EPC18 and EPC24 are given in Table 3.11.

Table 3.11 : Contributory values for "Inappropriate Shore Services".

HFACS-MMO sub-level	EPC2	EPC7	EPC18	EPC24
Inappropriate Shore Services	0.36	0.36	0.11	0.17
Contributory values	2.22	2.22	0.61	1.04

In order to quantify EPCs, all of the contributory values should be found within the matrix. After that, all contributory values with respect to each EPC are summed vertically in agreement with their belonging column (See: Table A.1). For instance, EPC1 is linked with *manufacturer deficiencies*, *supervisory violations*, *skill based error*, *knowledge based mistakes*, and *exceptional violations.* Their contributory values are calculated as; (3.40), (3.53), (5.47), (3.78) and (1.13) respectively. Hence, the EPC1 can be found as "17.30" as listed in Table 3.12.

Table 3.12 : Quantification of EPC1.

HFACS-MMO sub-level	EPC1
Manufacturer Deficiencies	3.40
Supervisory Violations	3.53
Skill Based Error	5.47
Knowledge Based Mistakes	3.78
Exceptional Violations	1.13
Total	17.30

Before interpolating new EPC values, an independent t-test is carried out to verify whether the results obtained are accurate to use in estimating the likelihood of human error. To accomplish this aim, a consensus of marine experts consisting of a marine director, 3 researchers and 2 engineers review and discusses all processes. Following this, due to its vital impact on the tests, a second-round is done in terms of making decisions again for the AHP submission. In the second round, the re-calculated EPCs and previous ones are compared, and the t-test is performed for these two data set. The two-tailed value, in conclusion, results as 0.951, which must be greater than 0.05. Since the maximum value for an EPC is determined as “17.00” in the original HEART, the obtained values for mmo-EPCs can be normalized in conjunction with this value. In this research, the maximum mmo-EPC value belongs to the mmo-EPC1 by 17.30.

In marine maintenance and operations, *inadequate supervision* and *planned inappropriate operation* are main factors that affect mmo-EPC2 (time shortage) and mmo-EPC13 (poor recording) in the “unsafe supervision” layer. In most of the accidents, the crew performs an operation without conducting a risk assessment or without considering potential hazards. Inadequate guidance from chief engineers and complacency on the inspections are the main reasons of them. Therefore, mmo-EPC11 (ambiguity in performance standard), mmo-EPC12 (misperception of risk) and mmo-EPC28 (lack of given importance) values are strongly increased.

In the “preconditions” of HFACS-MMO, there is no decisive difference between the sub-levels. Nonetheless, the impact of the *engine room physical environment* is relatively high as it mostly in connection with the poor or complex working environment. The most affected EPC is mmo-EPC5 (unreliabile instructions) from this sub-layer. The *engine room technological environment* considerably raises mmo-EPC26 (no progress monitoring), mmo-EPC3 (low signal-noise ratio) and mmo-EPC19 (insufficient data variety) due to deficiencies or dysfunctionalities of critical devices. The *condition of operator* can be very variable thus it affects several EPCs such as mmo-EPC27 (physical capabilities exceeded), mmo-EPC29 (emotional stress), mmo-EPC30 (ill-health), mmo-EPC31 (low workforce morale), mmo-EPC35 (irregular work-sleep cycle) and mmo-EPC38 (improper age for perceptual tasks). The *engine room crew management* influences mmo-EPC13 (poor recording) value, however other related EPCs are not influenced substantially.

The “unsafe acts” layer is arisen from *skill based error*, *knowledge based mistakes*, *rule based mistakes*, *routine violations* and *exceptional violations* of marine engineers. Ineffective malfunction detection, poor troubleshooting, inadequate maintenance of the equipment, violating the operational procedures, involving hazardous actions are the most frequent cause types of the engine room, according to the accident investigation reports.

Table 3.13 : Comparison of different method's EPC values.

EPCs	MMOHRA (2020)	SOHRA (2016)	HEART (1988)	NARA (2004)	CARA (2007)	RARA (2013)
EPC1	17.00	17.00	17.00	20.00	20.00	17.00
EPC2	14.03	14.01	11.00	11.00	11.00	11.00
EPC3	3.66	3.31	10.00	10.00	N/A	10.00
EPC4	5.78	8.72	9.00	9.00	N/A	9.00
EPC5	10.47	5.76	8.00	N/A	N/A	8.00
EPC6	1.13	2.64	8.00	N/A	N/A	8.00
EPC7	4.63	2.23	8.00	9.00	N/A	8.00
EPC8	1.58	14.45	6.00	6.00	6.00	6.00
EPC9	4.06	5.29	6.00	24.00	24.00	8.00
EPC10	4.08	11.00	5.50	N/A	N/A	5.50
EPC11	1.37	8.60	5.00	N/A	N/A	5.00
EPC12	4.00	12.51	4.00	N/A	N/A	4.00
EPC13	14.53	12.55	4.00	4.00	5.00	4.00
EPC14	1.96	6.72	4.00	N/A	N/A	N/A
EPC15	8.17	10.03	3.00	8.00	N/A	3.00
EPC16	1.50	8.42	3.00	3.00	5.00	3.00
EPC17	5.80	2.79	3.00	10.00	3.00	3.00
EPC18	2.60	2.15	2.50	2.50	N/A	2.50
EPC19	1.63	2.74	2.50	N/A	N/A	N/A
EPC20	2.59	2.88	2.00	N/A	N/A	N/A
EPC21	6.91	3.62	2.00	2.00	N/A	N/A
EPC22	1.06	1.64	1.80	N/A	N/A	1.80
EPC23	2.07	5.69	1.60	N/A	1.60	N/A
EPC24	3.64	1.17	1.60	N/A	N/A	N/A
EPC25	2.08	1.22	1.60	N/A	N/A	1.60
EPC26	3.26	3.28	1.40	2.00	N/A	N/A
EPC27	2.68	4.35	1.40	N/A	N/A	1.40
EPC28	2.83	2.56	1.40	N/A	N/A	1.40
EPC29	2.84	1.59	1.30	2.00	5.00	2.00
EPC30	1.47	0.89	1.20	N/A	N/A	N/A
EPC31	2.04	3.00	1.20	2.00	2.00	1.20
EPC32	1.24	9.43	1.20	N/A	N/A	N/A
EPC33	1.65	9.90	1.15	8.00	N/A	8.00
EPC34	1.90	2.63	1.10	N/A	N/A	1.10
EPC35	1.43	10.30	1.10	N/A	N/A	N/A
EPC36	1.02	3.85	1.06	N/A	N/A	N/A
EPC37	1.48	4.14	1.03	N/A	N/A	N/A
EPC38	1.86	3.61	1.02	N/A	N/A	N/A

Skill based errors make major contribution to the mmo-EPC1 (unfamiliarity) and mmo-EPC15 (new or inexperienced operator) values. *Knowledge based mistakes* also strongly increases mmo-EPC1 (unfamiliarity) value. *Routine violations* are usually connected with the recording deficiencies on-board a ship; hence it significantly influences mmo-EPC13 (poor recording) value. *Rule based violations* can be resulted from instruction based deficiencies, so mmo-EPC4 and mmo-EPC5 are increased. Moreover, such mistakes increase likelihood of human error where the reversibility of task hierarchy is difficult or certain judgments are needed.

Therefore, mmo-EPC7 (task irreversibility) and mmo-EPC24 (absolute judgment required) are also affected by this sub-layer. Hence, quantified mmo-EPC values have only a slight difference with the values of their previous form, so the results are not changed marginally during the normalization process. Eventually, the derived mmo-EPC values for MMOHRA is shown in Table 3.13 in comparison with the SOHRA, HEART, NARA, CARA and RARA.

Because the mmo-EPC values are specific for maintenance and operations in marine engineering, there are several differences with the SOHRA, which is proposed by Akyuz et al. (2016). Some crucial EPCs such as EPC1 (lack of familiarity), EPC2 (time shortage), EPC13 (poor recording) and EPC15 (unexperienced engineers / operators) are, nevertheless, notable agreements. Clearly, lack of familiarity is still the most crucial factor affecting operational safety in all domains, irrespective of the sectoral features. Accordingly, lack of time fundamentally increases the probability of human error in each discipline. Bad documentation performed on a report by another engineer (EPC13) has a significant impact on engine room duties. Compared to SOHRA, mmo-EPC13 has a difference in marine engineering operations due to the fact that all types of log-books and journals are critical on-board instruments. The value received by EPC15 (inexperienced engineer / operator) in the NARA is very similar to the mmo-EPC15, which reflects the nuclear industry based EPCs intended by Kirwan et al. (2004). The most increased mmo-EPC value in comparison to SOHRA is the mmo-EPC5 (unreliable instructions). The reason is the fact that engine room based ship accidents are much more vulnerable to instruction deficiencies. Mostly, this type of causes directly leads accidents. Similarly, the improper supervisor guidance which leads to dangerous or improper procedures is also largely increased (EPC21). It is obvious that unsafe engine room procedures are almost twice as dangerous as compared with the other shipboard operations. As another oversight issue in marine engineering activities, insufficient inspection (EPC17) in the engine room is fairly decisive. For this reason, it is necessary to carry out routine inspections and system monitoring tasks with high awareness. With regard to these findings, it can be seen that engine room supervisors and other managers have a major role to play in avoiding marine casualties. As another result, the likelihood of error increases considerably when compared to other shipboard activities, when a given function demands absolute judgment beyond the capabilities of the engineer (EPC24). The responsible engineer should be aware of the possible hazards of an operation in these situations so that he/she can decide on alternate solutions (i.e. finding assistance, delaying or canceling the operation).

In the literature, Islam et al. (2017) has also proposed specific EPCs for marine engineering maintenance operations. They have also reviewed the EPC descriptions, which have been taken into account in this study along with some other papers. Islam et al. (2017) have determined specific EPCs via judgments of experts who have more than 5 years of on-board ship experiences. The experts have revised the 37 out of 38 EPCs of HEART which was proposed by Williams (1988). By this aspect, the structure of MMOHRA differs substantially via establishing a database with the most recent marine engineering maintenance and operations related ship accidents. Since 435 causes are derived from the past accidents, the role of expert judgments are minimizing whilst the influence of past accidents are maximizing in order to obtain more accurate mmo-EPC values. However, research outputs could have different findings in accordance with the utilizing database as well as involving methods that taken advantage. For this reason, the mmo-EPC values of this study can be updated when there is considerable amount of new accident reports are acquired in the databases of maritime accidents.

3.3 Code of Good Practice

The application of the HRA depends on the data obtained from marine experts. Marine experts should select the existing EPCs along with the most proper GTT for each sub-task. Moreover, they should conduct APOA calculation when there are more than one EPC over a sub-task. All these efforts can take a long time, thus more automized calculation process is required. For this reason, a rule based practical MMOHRA tool is introduced under this chapter.

3.3.1 Rule Base for GTTs

GTT selection is a complex task for the supervisors who are responsible to take safety precautions prior to a ship engine room operation. The complexity of this process is arisen from the long descriptions of GTTs (See: Table 3.1). For this reason, it takes a long time to decide if the GTT of a task should be categorized as A, B, C, D, E, F, G, H or M.

	Complex Task & Rapid Operation	Simple Task & Rapid Operation	Complex Task & Not Rapid Operation	Simple Task & Not Rapid Operation
Unfamilliar & No Support	A	B	B	E
Unfamilliar & With Support	A	D	C	E
Familliar & No Support	B	D	C	G
Familliar & With Support	F	G	F	H

Figure 3.4 : GTT selection matrix.

When looking into descriptions of GTTs, there are four important aspects come into prominence. These aspects are *i) Task complexity, ii) Task pace, iii) Unfamilliarity, iv) Operational support & aid*. Since the descriptions are established on four different aspects, it is possible to make a matrix which can be utilized for the rule base of the GTT selection. Thus, in the light of these descriptions and these four aspects, a matrix is established as seen in Figure 3.4.

After establishing the matrix, a rule base can be created according to the four aspects of GTT descriptions. Later, GTT selection can be made easily through this rule.
So the rules for GTT selection can be listed as:

- Rule 1: If **Unfamilliarity** is YES AND **Complexity** is YES AND **Rapidity** is YES AND **No Support** YES Then **A**

- Rule 2: If **Unfamilliarity** is YES AND **Complexity** is YES AND **Rapidity** is YES AND **No Support** NO Then **A**
- Rule 3: If **Unfamilliarity** is NO AND **Complexity** is YES AND **Rapidity** is YES AND **No Support** YES Then **B**
- Rule 4: If **Unfamilliarity** is YES AND **Complexity** is NO AND **Rapidity** is YES AND **No Support** YES Then **B**
- Rule 5: If **Unfamilliarity** is YES AND **Complexity** is YES AND **Rapidity** is NO AND **No Support** YES Then **B**
- Rule 6: If **Unfamilliarity** is YES AND **Complexity** is YES AND **Rapidity** is NO AND **No Support** NO Then **C**
- Rule 7: If **Unfamilliarity** is NO AND **Complexity** is YES AND **Rapidity** is NO AND **No Support** YES Then **C**
- Rule 8: If **Unfamilliarity** is YES AND **Complexity** is NO AND **Rapidity** is YES AND **No Support** NO Then **D**
- Rule 9: If **Unfamilliarity** is NO AND **Complexity** is NO AND **Rapidity** is YES AND **No Support** YES Then **D**
- Rule 10: If **Unfamilliarity** is YES AND **Complexity** is NO AND **Rapidity** is NO AND **No Support** YES Then **E**
- Rule 11: If **Unfamilliarity** is YES AND **Complexity** is NO AND **Rapidity** is NO AND **No Support** NO Then **E**
- Rule 12: If **Unfamilliarity** is NO AND **Complexity** is YES AND **Rapidity** is YES AND **No Support** NO Then **F**
- Rule 13: If **Unfamilliarity** is NO AND **Complexity** is YES AND **Rapidity** is NO AND **No Support** NO Then **F**
- Rule 14: If **Unfamilliarity** is NO AND **Complexity** is NO AND **Rapidity** is YES AND **No Support** NO Then **G**
- Rule 15: If **Unfamilliarity** is NO AND **Complexity** is NO AND **Rapidity** is NO AND **No Support** YES Then **G**
- Rule 16: If **Unfamilliarity** is NO AND **Complexity** is NO AND **Rapidity** is NO AND **No Support** NO Then **H**

Table 3.14 : An example of inputs for GTT selection.

Operational Tasks	Unfamilliarity	Complexity	Rapidity	No support	GTT
#Task1	✓				E
#Task2		✓		✓	F
#Task3			✓		G
#Task4			✓		G
#Task5			✓		G
#Task6	✓			✓	E
#Task7	✓	✓		✓	B
#Task8	✓	✓			C
#Task9					H
#Task10	✓		✓	✓	B

According to this rule base, marine experts can only fulfill a form similar to which shown in Table 3.14. Thus, GTT selection can perform simpler and smoothly.This rule base can be utilized not only via MMOHRA but also other HRA methods' GTT selection process.

3.3.2 Rule Base for EPCs

EPC selection is more complex task than GTT selection for the experts who are responsible to take safety precautions for a specific operation. Since there are 38 different EPCs in MMOHRA, supervisors should think all EPCs for each sub-task in safety probability calculations. Hence, likewise the GTT selection process; it takes a long time to determine EPCs in a certain time period. Therefore, steps of an operational task in the engine room classified into some different groups such as; lifting coverings, equipment disassembly, equipment transfer, equipment alignment, measurement, cleaning, inspection, repair & replacement, equipment re-assembly, test & control. A comprehensive overhaul operation may contain all of these sorts of task descriptions, however simple operations may not. Therefore, the supervisors should specify the overall conditions at the beginning of an operation at once. According to the task steps, the EPCs which can affect the operational safety can be automatically determined in accordance with the matrix in Table A.2. Therefore, EPCs can be assigned instantly and dynamically via a practical tool.

3.3.3 Good practice tool of MMOHRA

The practical MMOHRA tool can be used prior to a maintenance operation in order to perform rapid and simpler HEP calculation. The tool consists of a software code which is written through “Python 3” language. Besides, SQLite database is also used in order to embed mmo-EPC and GEP value tables. In this regard, full coding system of the tool is given in Appendix B. According to this structure, the opening menu when run the tool is shown in Figure 3.5.

```
Welcome to MMOHRA Practical Calculation Tool

[1] Enter GTTs
[2] Enter EPCs
[3] View Existing GTTs
[4] View Existing EPCs
[5] Remove GTT
[6] Remove EPC
[7] Calculate
[Q] Exit

GTT: General Task Type
EPC: Error Producing Condition
```

Figure 3.5 : Opening menu of the programme.

As seen in the figure, adding GTT and EPC as well as removing them is possible. Users can also verify their inputs by viewing existing GTTs and EPCs. The calculation process can be initiated after all operational conditions are determined. There are 11 marine engineering task type for an operation as seen in Figure 3.6.

```
Your Choice: 1
The list of the marine engineering maintenance tasks:

                Task 1 : Lifting of Coverings or Blocks
                Task 2 : Disassembly of equipment
                Task 3 : Drill liquids from equipment
                Task 4 : Equipment Transfer
                Task 5 : Equipment Allignment
                Task 6 : Measurement of Equipment
                Task 7 : Cleaning of Equipment
                Task 8 : Inspection of Equipment
                Task 9 : Replacement, Repair & Maintenance
                Task 10: Assembly of Equipment
                Task 11: Test & Control of Equipment

                Please add a task type from the list.
                Please don't add if a task type doesn't included in your operation.
```

Figure 3.6 : Defined task types of marine engineering operation.

A user must enter at least one task type for a given operation. For each task type, then the system asks four different aspects of GTT to start rule base which is introduced in section 5.1. The user should only answer the questions about these aspects as illustrated in Figure 3.7

```
Task No: 2
Does Unfamilliarity exist for this task? Y or N: n
Is the task is complex? Y or N: y
The task must be performed rapidly? Y or N: y
Information support for this task doesn't exist? Y or N: n
Selected Task added
```

Figure 3.7 : GTT selection.

For instance, if user decides to select a GTT for *#Task No:2*, he/she should input “1”, at the opening menu, and then input “2” at the GTT selection menu. At this point, the tool asks about the four critical aspects specifically for this task; so when user anwers all these questions by entering “y” for yes and “n” for no; then the *#Task No:2* would be added by its determined GTT to the memory. This process is completely depends on the GTT tule base, as it is explained in the previous section. The memorizing is carried out via notepad files in order to reserve them permanently; until they are deleted from user.

```
Your Choice: 2
EPC No: 7
The EPC was added, press ENTER to proceed...
```

Figure 3.8 : EPC selection.

Similarly, a user can select all EPCs one by one prior to the operation by using the *#2: Enter EPCs* function at the opening menu. Then system simply asks a reply for the code of EPC in order to memorize it. If there is an EPC exists as “a need to approach to an engine room operation with opposing philosophy (EPC9)”, then the user should only input “9” and enter as seen in Figure 3.8.

After determining the GTTs and EPCs, then the calculation process can be conducted by entering “7” at the opening menu. Therefore, the tool automatically calculates the HEP values for each defined task types. According to the results, further analysis can be conducted.

3.4 Proposed Approach

The main difference of MMOHRA from the SOHRA is EPC values. Apart from these, the calculation process is very similar. There are also some differences can be seen in implementation process since the EPC and GEP descriptions are specialized.

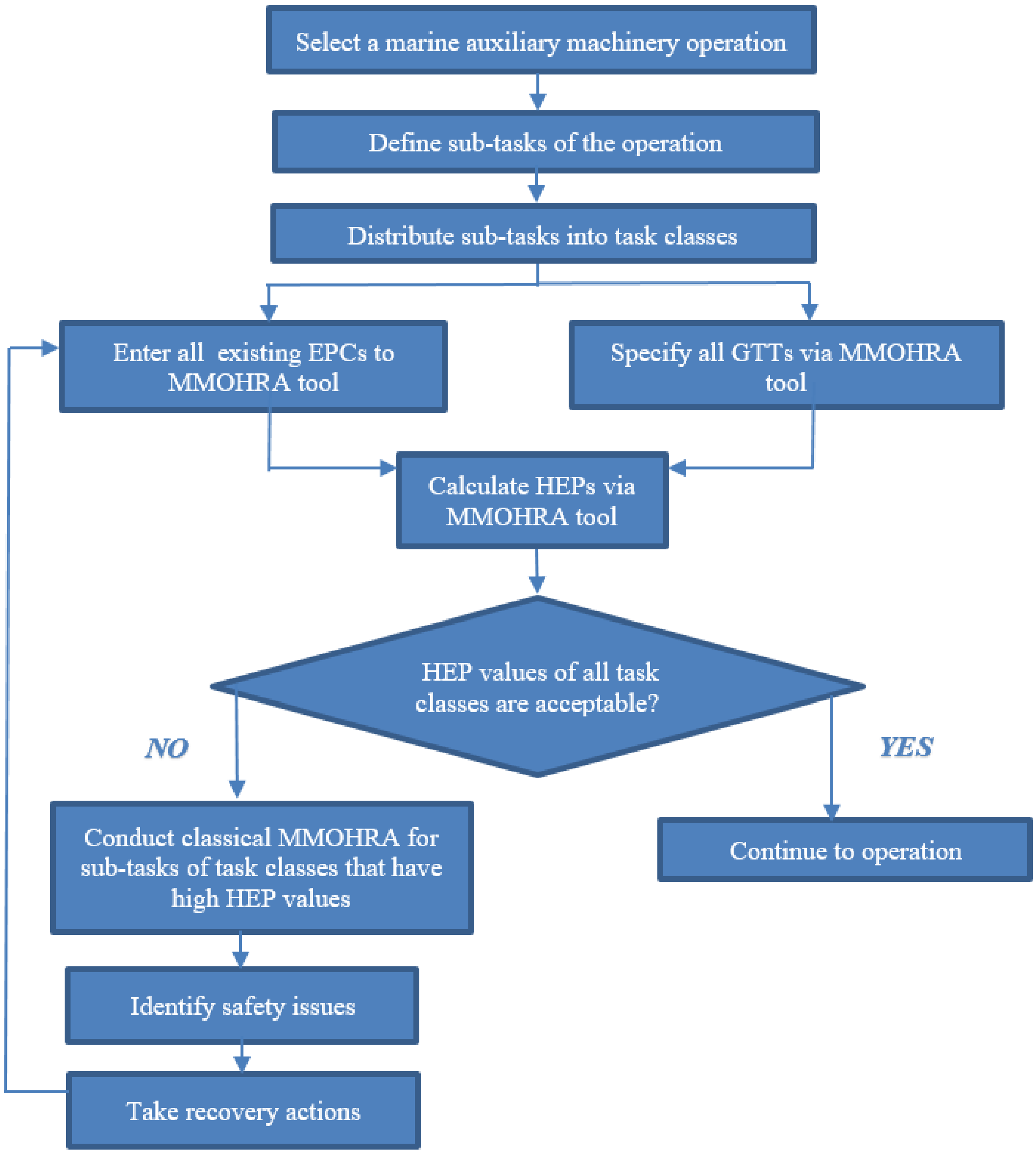

Figure 3.9 : Flowchart of the proposed approach.

- ***Step 1. Task Analysis***: The first step is to carry out task analysis to specify tasks of the maintenance operations. That is because, HEP value of each maintenance task should be found in order to obtain overall HEP value of maintenance operation.

- ***Step 2.* Analysing Safety Issues**: Operational conditions should be analysed and safety issues must be clarified. Such issues can be various conditions such as unreliable instruments, narrow working environment, fatigue, unfamiliarity of crew, and etc.
- ***Step 3*. GEP selection:** GTT and their nominal human unreliability values are shown in Table 3.15. In the MMOHRA, class M is eliminated, instead; if a suprintendent is not sure about the task type; the rule base in the "practical MMOHRA calculator tool" can be used. This is introduced in the next chapter elaborately.
- ***Step 4*. EPC selection:** This phase can be carried out by the members of a ship crew or marine superintendents. Similar with the GEP selection, the most appropriate EPCs for each task should be determined. These EPCs should be chosen from the list of thirty-eight possible EPCs along with the values of MMOHRA.

Table 3.15 : General task types and their values.

GTT	Nominal Human Unreliability
A	0.55
B	0.26
C	0.16
D	0.09
E	0.02
F	0.003
G	0.0004
H	0.00002

In the good practice tool of MMOHRA, all EPCs are selected for the whole operation, instead of carrying out for each task. The tool can calculate this automatically in accordance with the type of the maintenance task.

- ***Step 5.* APOA calculation**: If there are more than one EPC selected for a task, the APOA calculation is needed to specify priority of EPCs. In this way, more accurate data can be obtained. The APOA calculation determines proportion effect of each EPC.

- ***Step 6.*** **HEP calculation:** HEP value should be calculated for each operational task. For this process, equation (3.1) can be utilized and calculated accordingly, as in HEART and SOHRA techniques.

4. CASE STUDIES

In this chapter, three different case studies are introduced in order to demonstrate how to apply MMOHRA to the marine maintenance and operations. These applications are also made to verify the MMOHRA's functionality. Moreover, case study results are compared with the SOHRA approach. The first case is about a simple three rotor screw pump overhaul operation. In the second case, HFO separators of five different ships are examined. In the third case, a diesel generator overhauling operation is interrogated. Specific discussions are also made under relevant sections of each case study.

4.1 Case 1: Screw Pump Overhaul

In this section, human factor is analysed via SOHRA and MMOHRA without utilizing good practice tool. The main objective of this case is to make clear comparison results between these two approaches.

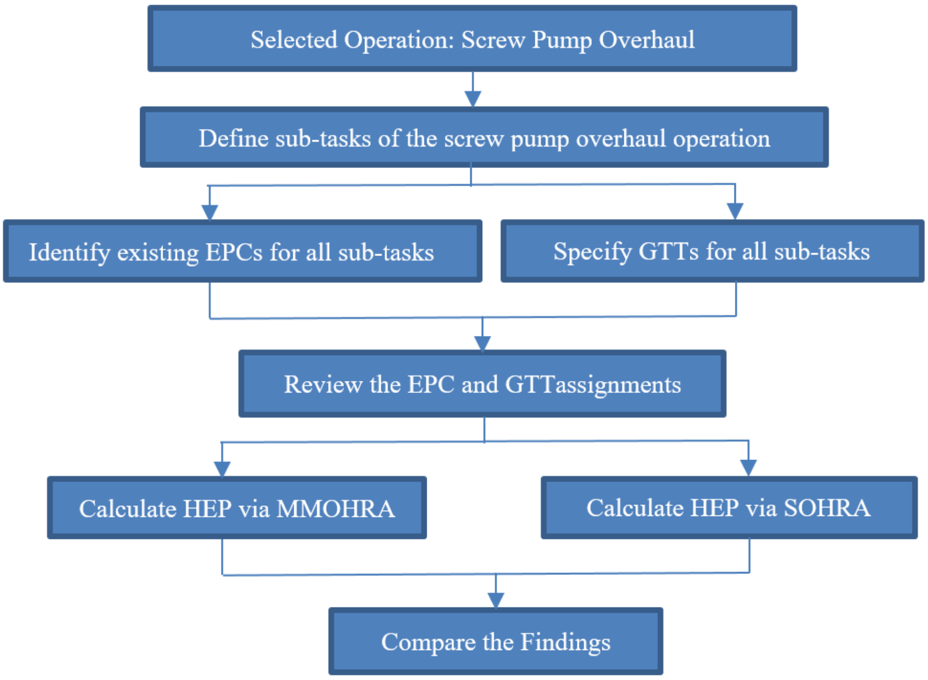

Figure 4.1 : Flowchart of the case study.

Since the main difference is EPC values, this section can also give broad idea how the newly found EPCs affect the results when comparing with the SOHRA's. In accordance to this objective, the framework of this case is shown in Figure 4.1.

4.1.1 Operating conditions

On a general cargo vessel, which has a carrying capacity of 2997 mtonnes, a three-rotor screw pump overhaul was scheduled. The vessel was built in 2008. Ten days before the operation, the 3rd engineer officer was assigned onboard. The weather was decent at the time of the overhaul and the sea-state was calm. Engine room space was quiet but the work area is narrow and messy. In addition, some of the tools needed for the maintenance tasks are in poor condition. The maintenance manual contains too much knowledge for the engineers, and can be confusing. However, the remainder of the conditions can be considered as reasonable and sufficient for the operation.

4.1.2 Analysis of operations

Tasks of the screw pump overhaul process are specified according to the first step of MMOHRA. Later, there are eleven tasks are identified as listed in Table 4.1. Afterwards, the initial conditions are reviewed and clarified. According to this analyse, corresponding EPCs are identified.

Table 4.1 : Comparative HEP values for SOHRA and MMOHRA.

Tasks	Task Descriptions	EPC	Generic Task Types	HEP Values of SOHRA	HEP Values of MMOHRA
T1	Close suction and discharge valve	EPC33	H	1.98E-04	3.30E-05
T2	Remove bolts & nuts of motor coupling and pipe flange	EPC 15, 23	G	7.36E-03	2.82E-03
T3	Remove pump foundation bolts	EPC 15, 23	G	7.36E-03	2.82E-03
T4	Remove impeller lock & nuts	EPC 15, 23	G	7.36E-03	2.82E-03
T5	Clean and inspect: bolts, lock, nuts and impeller	EPC 15	F	3.00E-02	2.45E-02
T6	Remove mechanical seal	EPC 15, 23	F	5.52E-02	2.11E-02
T7	Remove bearing cover and shaft	EPC 15, 23	G	7.36E-03	2.82E-03
T8	Clean and inspect bearing cover and shaft	EPC 15	F	3.00E-02	2.45E-02
T9	Replacement of mechanical seal and O'ring	EPC 4, 15	E	5.35E-01	3.11E-01
T10	Assemble all parts	EPC 4, 15	F	8.02E-02	4.66E-02
T11	Start a test work for pump and inspect for any abnormalities	EPC 4, 15	F	8.02E-02	4.66E-02

Thus, EPC4, EPC15, EPC23 and EPC33 are selected and assigned to the relevant tasks. Similarly, GTTs are specified. Further, the APOA calculation is carried out for the tasks of T2, T3, T4, T6, T7, T9, T10, T11. For instance, the impact of EPC15 and EPC23 is considered as they are evenly matched, the weights of both EPC are 0.5. Hence, all of the obtained values can be processed through equation 3.1 in order to reveal HEP values for MMOHRA.

4.1.3 Findings

The similar process can be conducted to obtain HEP values for SOHRA approach. In this case, the only difference is the EPC values between these two methods. Eventually, the final HEP values for these methods can be seen in Table 4.2.

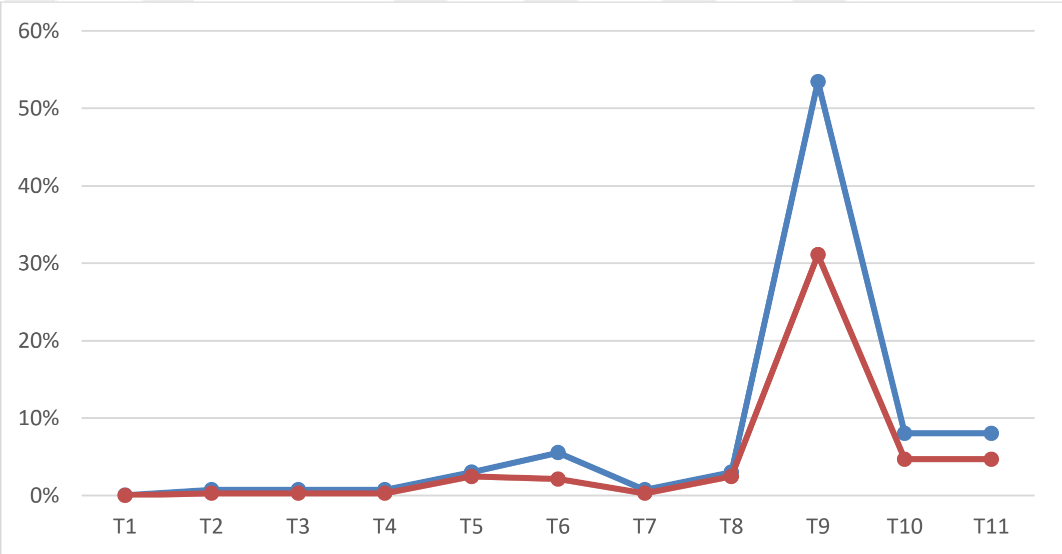

Figure 4.2 : Final HEP values of MMOHRA and SOHRA.

The findings for each task are illustrated in Figure 4.2. According to the obtained results, the most critical maintenance task is determined as T9: "Replacement of mechanical seal and O'ring". As the most critical value is 31% and 53.5% for MMOHRA and SOHRA respectively, the reasons for the T9's EPCs should be corrected primarily.

4.2 Case 2: HFO Separator Overhaul

A specific case study on purifier overhauling considers various on-board ship operating conditions. Since the selected operation involves a wide range of complications, careful consideration for ship and crew health is required. This section performs a comprehensive human reliability analysis for HFO purifier on-board ship overhaul process.

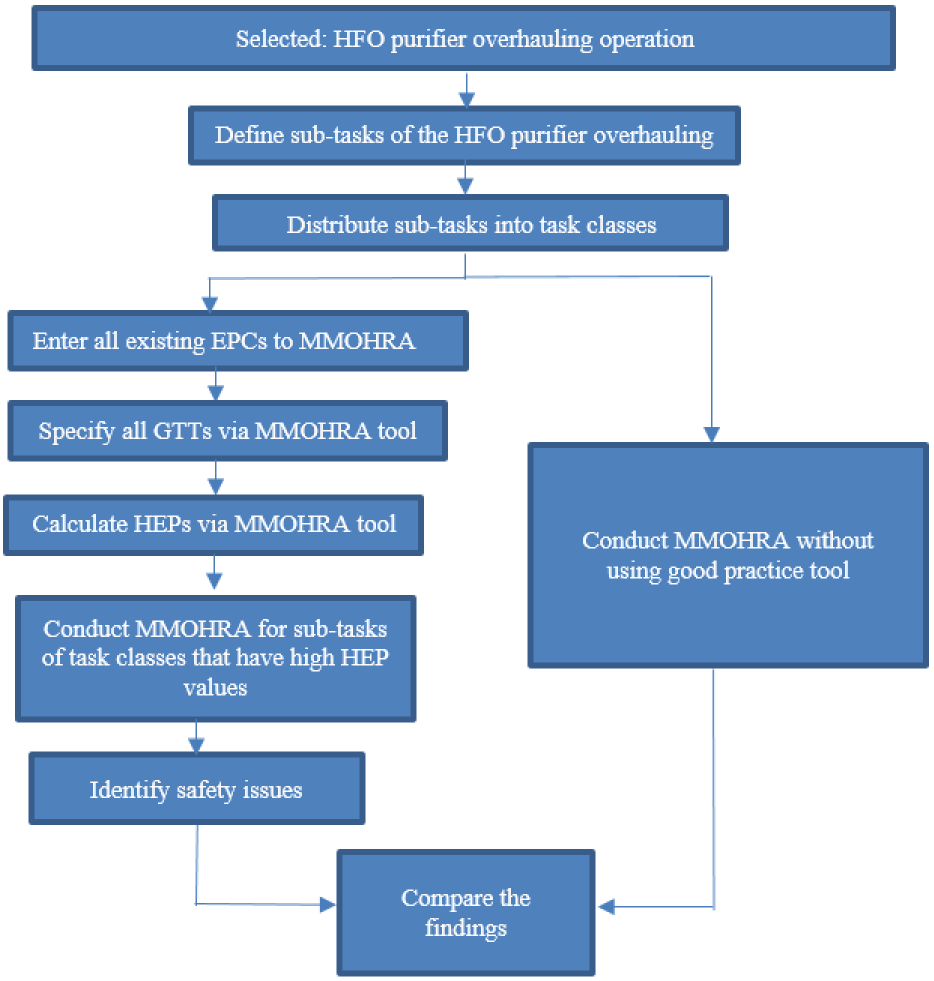

Figure 4.3 : Flowchart of the case study.

A HFO purifier's principal objective is to separate water and solid impurities from oil in order to avoid ineffective combustion (Mitsubishi, 1983). Fuel can contain high levels of catalytic fines or other impurities that can result in very costly damage to main engine components due to poor maintained purifier (Raptodimos and Lazakis, 2016). For this reason, the responsible crew conducts an HFO purifier overhaul if some failures or anomalies are detected, namely; excessive vibration, overflow, worn gear, improper motor speed etc. (Lazakis et al, 2017; Kandemir and Celik, 2017b).

Furthermore, the HFO purifier overhaul process has some specific safety precautions due to the working concept of purifier due to strong centrifugal force. False handling is thus very risky for both human health and machinery operations (Mitsubishi, 1983).

For this reason, this case meticulously examines the HFO separator overhauling operation in five different ships. The flowchart of the case study is given in Figure 4.3. In this case, rule based tool is utilized for MMOHRA and classical MMOHRA is implemented. In conclusion, a comparison between rule based MMOHRA and classical MMOHRA is provided.

4.2.1 Operating conditions

Since the real case study on HFO purifier overhauling considers different operating conditions on-board selected five ships in a dry bulk fleet; the conditions of all ships are given below.

SHIP-A is a general cargo ship and capable of carrying approximately 10,500 mt of freight. The ship was built in 1997. The HFO purifier overhaul process was conducted at sea voyage. The operation was attended by second engineer, donkeyman, and oiler. The weather was warm at the time of the overhaul and the sea-state was smooth. The overhaul process began in the morning and it was done around noon time. The crew was very tired due to previous operations. Engine room environment was noisy but other conditions can be considered as adequate level.

SHIP-B is a bulk carrier ship with a load carrying capacity of approximately 52,800 mtons. The ship was constructed in the year 2001. HFO purifier overhauling activity was performed at the port. Second engineer, third engineer, donkeyman and wiper were involved in the overhauling. The weather was good at the time of the overhaul and the sea-state was calm. The process of overhauling started in the morning and it was done by evening time. The crew was not tired too much, as they had been well resting before service. Engine room climate was calm, and the working environment was in adequate level.

SHIP-C is a general cargo ship with a cargo size of approximately 5.320 mtons. The ship was built in 2007. The overhauling was completed at the port. Chief engineer and second engineer involved in the process. At the time of overhauling, the temperature was 15 centigrade degrees and the sea state was calm. The operation began by morning time and was completed about the evening. The crew was not exhausted, can be considering in good level. Engine room environment was not noisy and working environment was satisfactory.

SHIP-D is a bulk carrier with a load carrying capacity of approximately 38,850 mtons. The ship was constructed in 1995. The overhaul was completed at sea voyage. Second engineer, third engineer, and donkeyman conducted the operation. The temperature was 11 centigrade degrees at the time of the overhaul and the sea state had low swell. The activity started in the morning and it was completed by the evening. The crew's state was “okay”. Engine room environment was calm, and working conditions are adequate.

SHIP-E is a bulk carrier ship with a cargo carrying capacity of approximately 18,700 mt. The ship was constructed in the year 2001. The overhauling was completed at anchor. Second engineer, third engineer, donkeyman, oiler and wiper participated in the process. The weather was 25 centigrade degrees with a moderate breeze (windy about 10 knots speed) at the time of overhaul, and the state of the sea was rough. The operation started afternoon time and it was completed in the evening. The crew was not exhausted. Engine room atmosphere was fairly noisy and working condition was adequate.

4.2.2 Analysis of operations

Hierarchal task analysis for HFO purifier overhaul is provided in Table 4.2. As seen in the table, the process of HFO purifier overhaul operation comprises of six main steps (inspection, dismantling, cleaning, replacement, assemblying and test & control) and thirty-seven sub-steps of all these task classes.

Table 4.2 : Operation steps of HFO purifier overhaul.

Step	Operation	Task Class
A1	The machine has to completely stop	INSPECTION (8)
A2	Power supply must be turned off	
A3	All valves on the system must be closed	
A4	The pipes and main body are heated to high temperature by the fuel oil	
A5	Not any of the operation should be carried out without having in instruction manual,	
A6	Check all specials tools belongs to the purifier are available and ready for use	
A7	Dismantle the sludge cover	DISMANTLING (2)
A8	Dismantle of the Bowl	
A9	Withdrawing Bowl;	
A10	Withdraw of the horizontal shaft	
A11	Withdraw of The Water Supply Device	
A12	Withdraw of The Vertical Shaft	
A13	Dismantle of the gear pump, check gears and replace it if necessary, replace the bearing bushes, O-rings, oil seal and reassembly	
A14	Vertical shaft; check of the spiral gear and teethes, replace bearings, replace the O-rings replace of the upper springs on the upper	
A15	Water supply devices; Clean all parts	CLEANING (7)
A16	Horizontal shaft; Replace bearings, replace spiral gear if necessary, replace O-rings, replace collars, replace friction boss	REPLACEMENT (9)
A17	Bowl; Clean of the bowl, clean discs, clean of the gravity disc, replace of the O-rings and main seal ring, replace the pilot valve	
A18	Clean of the sludge cover, main body, gear case and etc.	CLEANING (7)
A19	Assemble of the horizontal shaft's components with new O-rings.	ASSEMBLY (10)
A20	Assemble of the vertical shaft's components with new O-rings	
A21	Assemble of the electric motor with friction boss	
A22	Assemble of the gear pump with safety joint to the horizontal shaft	
A23	Assemble of the water supply device with new O-rings	
A24	Assemble of the bowl unit with sub components of it and O-rings.	
A25	Assemble of the bowl with new bowl bush to the vertical shaft and fix of it water supply device	
A26	Assemble of the sludge cover with new O-rings	
A27	Assemble of the sealing water tube and fuel oil inlet and outlet connecting pipes	
A28	Refill new lubricating oil inside to the gear case	TEST & C (11)
A29	The purifier has many screw coupled parts. At time of reassembly check that all these parts have been thoroughly tightened	
A30	All of the O-rings should not be damaged while on reassemble and are in good condition	
A31	Lubrication oil level check should be done before than start-up	
A32	Electrical motor direction of rotation should be checked and verified.	
A33	When purifier is operating, vibration checks should be carried out	
A34	While purifier is operating, amperage check should be done from the main switchboard	
A35	After running of the purifier check discharge sludge procedure are operative	
A36	After running of the purifier check fuel oil separating procedure are operative.	
A37	Leakage control of the pipe connections should be checked while purifier is running	

4.2.3 Findings

The conditions of all ships are reviewed with responsible experts and the initial safety issues are entered to the practical calculation tool. Besides, GTTs of all overhauling operations are determined in accordance with the task classifications. Eventually, the first results from the tool are listed in Table 4.3. The notations of the table signal very low (VL), low (L), medium (M), high (H), and very high (VH) HEP values for the determined task classes.

Table 4.3 : HEP scales of ships via good practice tool.

Task Class	HEP scales of ships				
	A	B	C	D	E
2	VL	VL	**VH**	**VH**	**VH**
7	VL	VL	VL	VL	VL
8	**H**	**VH**	**VH**	VL	**VH**
9	**VH**	**VH**	**VH**	**VH**	L
10	**VH**	**H**	**VH**	L	M
11	**H**	L	**VH**	VL	**VH**

High and very high HEP values (probabilities more than 25%) are considered as the task groups that require further analysis. For this reason, next phase of the case study needs closer and detailed analysis. Hence, each sub-tasks which belong to the high HEP value group are conducted in a conventional way.

In the traditional approach, each sub-task should be identified by experts. This means that the almost half of the sub-tasks can be eliminated by the good practice tool. Since this case compares these two different processes, the time consumptions are also provided in the findings section. In this phase, all assigned EPCs and GTTs are shown in Table 4.4. In this table, the assignments with bold puntos indicate the assignments which should made within the two approaches. The rest of the assignments address only the classical MMOHRA.

Table 4.4 : Selected EPCs and GEPs for all ships.

Step	Generic Task Types of Ships					EPC of Ships				
	A	B	C	D	E	A	B	C	D	E
A1	**G**	**G**	**F**	*F*	**F**	**EPC 2,10**	**EPC 16,17**	**EPC 2,4**	*EPC 8,9,16*	**EPC 2,4,22,31**
A2	**G**	**F**	**F**	*F*	**F**	**EPC17**	**EPC 16,17**	**EPC 10,13**	*EPC 9,14,20*	**EPC 1,15**
A3	**E**	**G**	**G**	*G*	**F**	**EPC 15,22**	**EPC 15**	**EPC 1,4**	*EPC 16*	**EPC 1,4,8**
A4	**F**	**C**	**G**	*F*	**G**	**EPC12,15,16**	**EPC 24**	**EPC 20,25**	*EPC 8,17*	**EPC 20**
A5	**E**	**E**	**F**	*E*	**F**	**EPC 22**	**EPC 9,15**	**EPC2,16**	*EPC 9*	**EPC 15,20**
A6	**F**	**F**	**G**	*F*	**G**	**EPC 2**	**EPC 9**	**EPC 19,23**	*EPC 1,4*	**EPC 1,2,19**
A7	*F*	*G*	**E**	**E**	**F**	*EPC 1,10*	*EPC 2*	**EPC 27**	**EPC 9,22**	**EPC 1,12**
A8	*F*	*H*	**G**	**G**	**G**	*EPC 15,22*	*EPC 2,13*	**EPC 1,2**	**EPC 9,16,22,35**	**EPC 1,2**
A9	*F*	*E*	**F**	**G**	**F**	*EPC 22*	*EPC 10*	**EPC 5**	**EPC 9,16,22,35**	**EPC 1,15**
A10	*E*	*E*	**F**	**E**	**F**	*EPC 2,22*	*EPC 11*	**EPC 1,15**	**EPC 7**	**EPC 1,13**
A11	*F*	*D*	**F**	**G**	**F**	*EPC 1,11*	*EPC 22,25*	**EPC 1,15**	**EPC 9,16,22**	**EPC 1,13**
A12	*G*	*H*	**F**	**E**	**F**	*EPC 2*	*EPC 2,38*	**EPC 1,15**	**EPC 7**	**EPC 1,13**
A13	*G*	*H*	**G**	**D**	**F**	*EPC 11,13*	*EPC 10,15*	**EPC 1,2**	**EPC 3,6,7**	**EPC 1,15**
A14	*G*	*G*	**G**	**D**	**F**	*EPC 17,38*	*EPC 13,15*	**EPC 1,2**	**EPC 3,6,7**	**EPC 1,15**
A15	*F*	*H*	*G*	*G*	*F*	*EPC 1,38*	*EPC 2,14*	*EPC 20,22*	*EPC 4,8,22*	*EPC 1,15*
A16	**C**	**G**	**F**	**C**	*F*	**EPC 22**	**EPC 2,13**	**EPC 9,23**	**EPC 7**	*EPC 1,23*
A17	**F**	**D**	**G**	**F**	*F*	**EPC 15**	**EPC 22**	**EPC 1,2,30**	**EPC 1,3**	*EPC 1,15*
A18	*G*	*G*	*F*	*G*	*F*	*EPC 22,25*	*EPC 15,22*	*EPC 4*	*EPC 2,14*	*EPC 4,9*
A19	**G**	**F**	**F**	*F*	*F*	**EPC 25**	**EPC 17,22**	**EPC 11,35,36**	*EPC 2,3,6*	*EPC 1,15,22*
A20	**E**	**G**	**F**	*F*	*F*	**EPC 14**	**EPC 22,25**	**EPC 11,35,36**	*EPC 2,3, 6*	*EPC 1,15,22*
A21	**G**	**G**	**G**	*E*	*F*	**EPC 2**	**EPC 22,33**	**EPC 9,22,27**	*EPC 9*	*EPC 1,15,22*
A22	**E**	**H**	**G**	*E*	*F*	**EPC 22,33**	**EPC 10**	**EPC 9,22,27**	*EPC 9*	*EPC 1,15,22*
A23	**E**	**E**	**F**	*F*	*F*	**EPC 2**	**EPC 17**	**EPC 1,2,9,22**	*EPC 9,16*	*EPC 1,15,22*
A24	**F**	**F**	**G**	*F*	*F*	**EPC 12,14**	**EPC 15,17**	**EPC 1,2,9,29**	*EPC9,16,22*	*EPC 1,15,22*
A25	**G**	**H**	**E**	*F*	*F*	**EPC 1**	**EPC 2,8**	**EPC 6,10**	*EPC 2,9*	*EPC 1,15,22*
A26	**G**	**H**	**F**	*F*	*F*	**EPC 15,24**	**EPC 14,22**	**EPC 1,16**	*EPC 4,8*	*EPC 1,9,16*
A27	**F**	**H**	**F**	*F*	*F*	**EPC 15**	**EPC 11,15**	**EPC 11,25,36**	*EPC 5,9,14*	*EPC 1,13*
A28	**G**	*G*	**F**	*F*	**F**	**EPC 17,23**	*EPC 1,17*	**EPC 4,15,28**	*EPC 8,14*	**EPC 1,4,35**
A29	**G**	*G*	**F**	*G*	**G**	**EPC 2**	*EPC 2,22*	**EPC 8,16,25**	*EPC 4,15*	**EPC 1,2,9**
A30	**F**	*H*	**F**	*G*	**F**	**EPC 15,22**	*EPC 12, 33*	**EPC 3,15,19,32**	*EPC 1,2*	**EPC 1,13,15,19**
A31	**E**	*H*	**E**	*G*	**F**	**EPC 38**	*EPC 1,10*	**EPC 25,28,31,34**	*EPC 14,29,31*	**EPC 1,13**
A32	**F**	*G*	**E**	*G*	**E**	**EPC 25**	*EPC 22*	**EPC 33**	*EPC 14,29,31*	**EPC 1**
A33	**G**	*E*	**E**	*G*	**F**	**EPC 31,38**	*EPC 17*	**EPC 3,17**	*EPC 14,29,31*	**EPC 1,14**
A34	**G**	*E*	**E**	*G*	**F**	**EPC 22**	*EPC 29,36*	**EPC 25,28,31,34**	*EPC 14,29,31*	**EPC 1**
A35	**H**	*G*	**F**	*F*	**F**	**EPC 10,33**	*EPC 22,38*	**EPC 1**	*EPC 1,2,6*	**EPC 1,12**
A36	**F**	*F*	**F**	*F*	**F**	**EPC 33**	*EPC 15*	**EPC 1,17**	*EPC 1,2,6*	**EPC 1,9**
A37	**G**	*H*	**F**	*G*	**F**	**EPC 17**	*EPC 2*	**EPC 2**	*EPC 1,2,6*	**EPC 1,13**

Since the assignments of all EPCs and GTTs are completed by the experts, calculation process can be initiated. For each step, the MMOHRA calculation is executed. The results are listed in Table 4.5. Similar with the previous tables, the values which are recommended for closer look by good practice tool are indicated as bold puntos, whilst the others belong to the traditional approach.

Table 4.5 : HEP values of MMOHRA.

Step	Ship-A	Ship-B	Ship-C	Ship-D	Ship-E
A1	**7.64E-03**	**3.81E-03**	**1.09E-01**	*1.32E-01*	**6.50E-02**
A2	**2.32E-03**	**2.68E-02**	**1.22E-01**	*2.94E-02*	**1.49E-01**
A3	**9.45E-02**	**4.01E-03**	**1.75E-02**	*3.37E-03*	**2.59E-01**
A4	**2.60E-02**	**1.87E-01**	**8.61E-04**	*4.39E-02*	**1.15E-03**
A5	**2.12E-02**	**2.07E-01**	**1.06E-01**	*1.06E-01*	**3.21E-02**
A6	**1.50E-03**	**1.59E-02**	**2.50E-03**	*1.31E-01*	**2.48E-02**
A7	*6.86E-02*	*5.60E-03*	**8.70E-02**	**8.30E-02**	**1.37E-01**
A8	*1.42E-02*	*1.02E-03*	**2.70E-02**	**9.13E-03**	**2.70E-02**
A9	*3.18E-03*	*2.20E-01*	**1.73E-02**	**9.13E-03**	**1.49E-01**
A10	*1.55E-01*	*1.72E-01*	**1.49E-01**	**4.46E-02**	**1.83E-01**
A11	*3.20E-02*	*1.86E-01*	**1.49E-01**	**3.71E-03**	**1.83E-01**
A12	*5.61E-03*	*3.46E-04*	**1.49E-01**	**4.46E-02**	**1.83E-01**
A13	*1.49E-02*	*6.60E-04*	**2.70E-02**	**3.54E-01**	**1.49E-01**
A14	*1.94E-03*	*1.50E-02*	**2.70E-02**	**3.54E-01**	**1.49E-01**
A15	*3.86E-02*	*5.79E-04*	*1.02E-03*	*8.39E-03*	*1.49E-01*
A16	**1.70E-01**	**2.12E-03**	**3.16E-02**	**3.57E-01**	*9.03E-02*
A17	**2.45E-02**	**1.47E-01**	**1.09E-02**	**5.82E-02**	*6.45E-02*
A18	*6.34E-04*	*2.90E-03*	*2.62E-02*	*9.81E-03*	*4.59E-02*
A19	**8.32E-04**	**7.50E-03**	**8.98E-02**	*4.76E-02*	*8.11E-02*
A20	**3.92E-02**	**5.86E-04**	**8.98E-02**	*4.76E-02*	*8.11E-02*
A21	**5.61E-03**	**5.30E-03**	**2.28E-03**	*1.06E-01*	*8.11E-02*
A22	**4.56E-02**	**2.20E-04**	**2.28E-03**	*1.06E-01*	*8.11E-02*
A23	**2.81E-01**	**2.51E-01**	**1.15E-01**	*4.44E-02*	*9.92E-02*
A24	**2.78E-02**	**3.13E-02**	**1.51E-02**	*3.08E-02*	*9.78E-02*
A25	**6.80E-03**	**1.16E-03**	**1.20E-01**	*7.08E-02*	*8.11E-02*
A26	**4.25E-03**	**1.02E-04**	**1.27E-01**	*1.13E-01*	*1.28E-01*
A27	**2.45E-02**	**5.29E-04**	**2.40E-02**	*5.42E-02*	*1.83E-01*
A28	**2.09E-03**	*4.12E-03*	**8.04E-02**	*8.95E-02*	**1.17E-01**
A29	**5.61E-03**	*3.25E-03*	**4.78E-02**	*1.07E-02*	**3.09E-02**
A30	**7.60E-02**	*7.43E-04*	**6.87E-02**	*2.70E-02*	**2.73E-01**
A31	**3.72E-02**	*1.08E-03*	**6.19E-02**	*2.30E-03*	**1.83E-01**
A32	**6.24E-03**	*6.56E-04*	**2.44E-02**	*2.30E-03*	**3.40E-01**
A33	**8.69E-04**	*5.58E-02*	**8.17E-02**	*2.30E-03*	**1.04E-01**
A34	**4.24E-04**	*8.63E-02*	**5.11E-02**	*2.30E-03*	**5.10E-02**
A35	**6.73E-05**	*1.22E-03*	**5.10E-02**	*1.61E-01*	**1.82E-01**
A36	**4.95E-03**	*3.00E-02*	**5.12E-02**	*1.61E-01*	**8.49E-02**
A37	**2.32E-03**	*2.80E-04*	**4.20E-02**	*2.15E-02*	**8.89E-02**

The final HEP values for the ships can be calculated in accordance with the task schedule. The task schedule for HFO sperator is dividied into three different time schedule: i) Tasks: A1-A12, ii) A13-A18, iii) A19-A37.

In this process, all tasks are dependent on the previous tasks. In other words, a task could not be initiated as long as previous task is not done. Hence, this system is called as a serial system. For this reason, the maximum HEP values in these three scheduled task groups should be summed to reach a final HEP value for a ship. The HEP values in percentage units for each serial connected task group is shown in Figure 4.4. In this figure, blue, red and green bars refer task group of A1-A12, A-13-A18 and A19-A37, respectively.

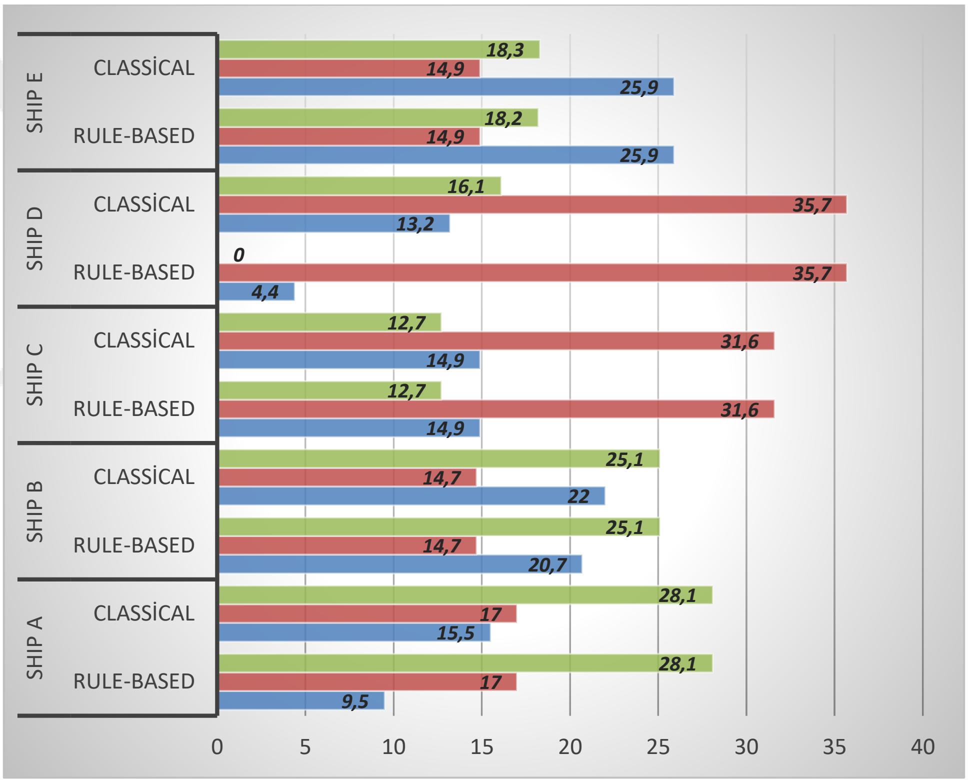

Figure 4.4 : Percentages of HEP values in terms of serial task groups.

According to this description, the final HEPs for all ships in the rule based MMOHRA is resulted as *5.46E-01* for Ship-A, *6.06E-01* for Ship-B, *5.92E-01* for Ship-C, *4.01E-01* for Ship-D and 5.90*E-01* for Ship-E. In the traditional MMOHRA; the final HEP values are *6.06E-01* for Ship-A, *6.18E-01* for Ship-B, *5.92E-01* for Ship-C, *6.50E-01* for Ship-D and 5.91*E-01* for Ship-E. The results show that rule based MMOHRA approach is reached the values as almost the same as that of the classical approach.

However, the results of Ship-D create a little exception towards this statement as the difference between the two findings is around 19%. This signals that the good practice tool of MMOHRA can be beneficial but it is still open for development.

The main objective of good practice tool is to minimize the time consumption during the application of MMOHRA for related experts or supervisors. The consumed times for each processes are listed in Table 4.6. As seen in the table, some processes are exactly the same such as pre-meeting, determining hierarchial task process, observing the conditions, reviewing the conditions. The values are average of five different ships which are measured during the HFO separator overhaul.

Table 4.6 : Timelines of MMOHRA applications.

Actions	**Classical Approach**
Pre-meeting	15
Determining hierarchial task process	55
Observing the operating conditions	35
Reviewing the conditions via meeting	10
Determining GTTs for each task	43
Determining EPCs for each task	121
Calculating final HEP values	38
TOTAL	***317 mins***
Actions	**Rule-Based Approach**
Pre-meeting	15
Determining hierarchial task process	55
Observing the operating conditions	35
Reviewing the conditions via meeting	10
Specifying task classes	6
Determining GTTs for task classes	5
Determining EPCs	7
Calculation to detect critical tasks	1
Determining GTTs for critical tasks	5
Determining EPCs for criticial tasks	61
Calculating final HEP values	21
TOTAL	***221 mins***

The analysis lasts *317 mins* through classical approach. Since the rule based approach is aimed to eliminate low HEP valued tasks, the initial findings are revealed in *134 mins*. If the conditions were adequate and EPCs are not many; the analysis can be finalized in *134 mins*. However, there are many EPCs in this case study; so the good practice tool is found several critical task classes. As a result, whole process takes *221 mins* with rule based MMOHRA due to requirement of further analysis towards many critical task classes. This means that good practice tool decreases the time consuming by 30% approximately when there are many EPCs. Moreover, the initial findings require 58% less time comparing the classical approach.

4.3 Case 3: Diesel Generator Overhaul

PMS is a widely used ship maintenance system which enables required actions to be carried out in conjunction with requirements of international maritime conventions and classification societies.

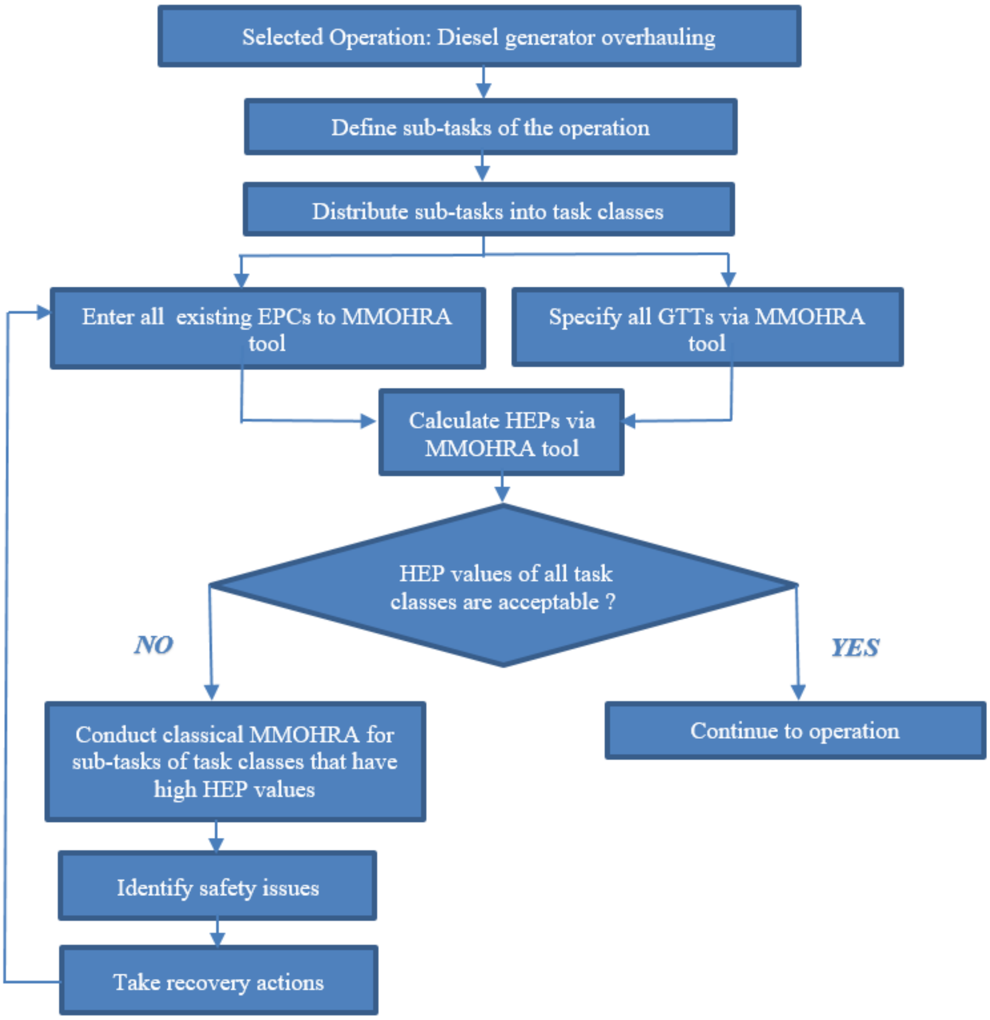

Figure 4.5 : Flowchart of the case study.

Since PMS represents an actual workload for the crew of a ship, relevant tasks must be performed properly at the right time. In PMS, time-based schedules and running hour-based maintenance tasks are intended to be maintained with the goal of minimizing possible risks that may result in breakdowns. That means that any machinery or equipment that is part of a PMS checklist must be maintained even if there is no expected failure. Such maintenance operations and PMS checklists are documented and managed properly as they are conducted by responsible staff to meet the ISM Code specifications (Kandemir and Celik, 2017a). At times, supervisory bodies such as Port State Control (PSC), classification societies, and shipowner firms audit the record books. In this case study, a HRA for a comprehensive marine auxilliary machine overhaul operation is conducted. According to the obtained tasks of the equipment, a PMS based maintenance approach is considered. This time, the proposed MMOHRA in this research is fully implemented. In this regard, the framework of this case stıdy is illustrated in Figure 4.5.

4.3.1 Operating conditions

A ship environment may vary by ship type, hull design, type of machinery & equipment, operator competency, operator experience, and weather conditions. Since the main objective of this research is to comprehensively assess the possible benefits of maintenance 4.0 in terms of human efficiency, this case study is chosen as it does not include severe circumstances such as very poor weather conditions, old workers, ill health or interrupted sleep cycle. Nevertheless, there are some difficulties for the ship crew. Some of the operators, for instance, are very experienced but some of them are not, so they may have trouble with certain tasks, particularly those that are not everyday jobs. Also, ship environment is selected as very commonly found in the maritime industry: an engine room with a medium level adequency. Similarly; the work area was neither large, nor small. However, several various tasks weren't spaced properly.

Since the selected auxiliary machine is a diesel generator, a bulk carrier ship with construction year 2001 and 53,000 (approximately) deadweight tonnage is selected. On board, a generator with a power of 720kW is introduced. Some instructions for the diesel generator appear out-of-date or unreadable according to the ship crew. The ship was at a port at the time of the operation in order to unload some of the freight. The estimated time for departure is given wrong for departure, so a time problem can occurr for some tasks of the operation. The weather conditions were good, the working area temperature was at the optimal level and the vessel didn't lurch. The ship's engineering officers / operators had 2-3 years of experience, their age was not old, and their health was good. In recent years they had overhauled one or two diesel generators. Crew working hours on the ship is met International Labor Organization (ILO) requirements. The sleep cycle of operators is at acceptable levels and only 3 hours passed since they woke up. The size of the working area was nearly enough for the overhauling operation. The area is not so clean, not so poor. Air compressors, some discharging pumps and boiler continue to work and they make some noise in this area. Some of the support tools for the overhauling operation were very old, so some tasks may require additional physical effort.

4.3.2 Analysis of operations

Ship diesel generators are essential for ship power generation. The energy generated is distributed to the main bus bar to feed a ship's electricity-supplied parts such as equipment, machinery, lighting and tools. Their maintenance operations are performed in a timely manner according to their operating concept and model size, i.e. 250 hours, 1000 hours, or 8000 hours. Furthermore, diesel generators are maintained daily through regular inspections which PMS needs. To carry out a detailed overhaul process, all the connected systems, valves, pumps and diesel generator components must be removed properly. It defines the list of the main tasks and subtasks for a thorough overhaul operation, also called a "major overhaul" (Detroit, 1979); (Mahon, 1992); (Weichai, 2009); (Woodyard, 2009); (Westerbeke, 2017); (Yanmar, 2013). In Table 4.7, the maintenance steps and task classifications of the case study are listed in details.

Table 4.7 : Operation steps of diesel generator overhaul.

Step	Operation	Task Class
T1)	Before overhaul, check power availability, available special tools, measuring tools, spare parts, power backs and team preparedness.	8 (INSPECTION)
T2)	Prepare working environment for overhaul: Isolation, Tagging, checking special tools, Operating Procedures & Tools, Values & Units, Part Assembly & Arrangement	
T3)	Open rocker arm cover, crank case and cam case doors.	2 (DISASSEMBLY)
T4)	Open cylinder head connections: water, lube oil, injector etc.	
T5)	Open Fuel Pump & connections to the head	
T6)	Remove cylinder head and its connections	
T7)	Remove Piston and main bearing	
T8)	Inspect timing gear	
T9)	Remove Cylinder Head & Cylinder head parts (including valves)	
T10)	Remove & Inspect seat	

Table 4.7 (continued) : Operation steps of diesel generator overhaul.

T11)	Remove valve guide & Starting air valve	
T12)	Remove Connecting rod & Big end	
T13)	Remove Liner & Clean seating surface	
T14)	Remove Thrust bearing	7 (CLEANING OF EQUIPMENT)
T15)	Remove Crank Gear, timing gear, governor	
T16)	Remove all pumps & valves	
T17)	Remove Air Cooler	
T18)	Clean & check Cylinder head and mountings	
T19)	Clean piston surface, bore, oil holes, ring grooves & Check connections.	
T20)	Clean liner, O-ring grooves & Check for cracks, polishing	
T21)	Clean & Check jacket frame	
T22)	Check Connecting Rod, Big End Parts	6 (MEASUREMENT)
T23)	Check Connecting Rod Hydraulic & Tie Bolts	
T24)	Check Crank Pin	
T25)	Inspect bearing shells	
T26)	Clean air cooler properly (by chemicals)	
T27)	Measure valve & seat angles of cylinder head	
T28)	Measure piston diameter & necessary piston parts	
T29)	Check Connecting rod bolts & Measure Big End Ovality	
T30)	Measure Crank pin	
T31)	Clean bearings properly	10 (ASSEMBLY OF EQUIPMENT)
T32)	Calibrate Liner and replace if necessary	
T33)	Measure shell thickness	
T34)	Measure gear backlash	
T35)	Clean Tappet	
T36)	Do crankshaft deflection	
T37)	Clean pin surface of bearing & Apply lube oil to smooth fitting	
T38)	Check liner, renew o-rings and assembly properly	
T39)	Clean & assembly piston and connecting rod	
T40)	Clean crank pin bearing shells & Fit them properly	7 (CLEANING)
T41)	Insert piston slowly. Tighten bolts.	
T42)	Check all cylinder head parts & assembly cylinder head	
T43)	Check & Clean Alternator including air filter, heater, voltage regulators	
T44)	Check water system & Close drain valves	
T45)	Check Lubricating Oil system & Engage turning gear for at least 30 mins	
T46)	Ensure fuel valves in order. Check pressure on local gauges.	
T47)	Check & inspect Air System to the diesel generator for any abnormality.	
T48)	Check oil levels, lubricating oil pumps	11 (TEST)
T49)	Ensure that all trips are properly set, auto-synchro is disabled.	
T50)	Do Procedure for Start & Test Engine.	
T51)	Monitor any abnormal noises & malfunctions. Record all parameters.	
T52)	Final check for any anomalies (Noise, temperature, crank case situation.	

Hence, the tasks of overhauling diesel generators are defined extensively on board a ship. The scope of the tasks is variable and there may be additional actions in several of those tasks. For example, T17 is about removing the air cooler; however, to complete this subtask, an operator should remove all pipes and connections from the air cooler, loose all relevant bolts and then carefully remove the air cooler.

4.3.3 Findings

Since the task classifications are specified and operating conditions are described, marine experts can determine GTTs and EPCs via practical MMOHRA tool. According to the MMOHRA tool, the initial results are obtained as listed in Table 4.8. In light of these first results, task class 10 (Assemblying) and 11 (Test & Control) have some high HEP values. The rest of the task classes has low HEP values so they are no longer considered in the next phase of the analysis.

Table 4.8 : HEP scales of task classes.

Task Class	HEP Scale
2	Low
6	Low
7	Very Low
8	Very Low
10	Very High
11	High

In order to determine HEP values of each sub-task, conventional approach is implemented in the next phase for task class 10 and 11. In consequence, Table 4.9. shows HEP values for operation steps of diesel generator overhauling calculated via MMOHRA. Since the main step is divided into sub-steps to find the final HEP value, the connection between the sub-tasks is established using probabilistic safety analysis and an analysis of the hierarchical tasks.

The results show that the dominance sub-task which increase the HEP of the task class 10 (Assemblying) is sourced by T32 (11.20%) due to EPC32 (*Inconsistent guidance, drawings or procedures for a specific task*). Followingly, T29 (9.86%) and T28 (9.01%) due to EPC17 (*Little or no inspection & test conducted for specific equipment/machinery by the supervisor*), EPC33 (*Poor, hostile and uncomfortable condition of the engine room*) and EPC34 (*Prolonged inactivity or highly repetitious cycling of low mental workload of the engineer*).

Table 4.9 : HEP values of diesel generator overhauling.

Step	GTT	EPC	HEP values
T27	G	EPC 34	7.60E-04
T28	E	EPC 17,33	9.01E-02
T29	E	EPC 17,34	9.86E-02
T30	G	EPC 15	3.27E-03
T31	F	EPC 22	3.18E-03
T32	D	EPC 32	1.12E-01
T33	G	EPC 19	6.52E-04
T34	G	EPC 20,34	1.04E-03
T35	G	EPC 35	5.72E-04
T36	F	EPC 33	4.95E-03
T44	E	EPC 4,6	4.98E-02
T45	E	EPC 2,14	2.57E-01
T46	F	EPC 17	1.74E-02
T47	G	EPC 18	1.04E-03
T48	G	EPC 34	7.60E-04
T49	G	EPC 14	7.84E-04
T50	E	EPC 2,3,16	2.57E-01
T51	F	EPC 3,12	1.71E-02
T52	E	EPC 34	3.80E-02

For the task group 11 (Test and control); T45 and T50 have critical HEP values with 25.7% due to EPC 2 (*A shortage of time available for error detection and correction in the engine room*), EPC3 (*The low signal-noise ratio due to noise in the engine room*), EPC14 (*No clear direct and timely confirmation of an intended action from a system in the engine room*), EPC16 (*Poor quality of information conveyed between engine room crew*).

Since the critical tasks are identified, recovery actions can be taken. All important EPCs, their short descriptions and recovery actions are shown in Table 4.10. These recovery actions can eliminate related EPCs for this overhauling operation however, further countermeasures are required for the company's next activities. When recovery actions are completed, the HEP of the task classes should be calculated again (See Figure: 4.5).

Table 4.10 : EPCs and recovery actions.

EPC	Short Description	Recovery Action
EPC2	Time Shortage	Allocated time for test & control actions are increased
EPC3	Low Signal-Noise Ratio	Alarm systems and sounds are maintained
EPC14	Poor System Feedback	Lubricating oil system feedback units are renewed
EPC16	Impoverished information	Chief engineer starts to control interval meetings during the shift changes in order to eliminate corrupted information
EPC17	Inadequate inspection	Inspection procedure is reviewed and responsible engineer is warned
EPC32	Inconsistent drawings	Liner replacement drawings are corrected by the updated information.
EPC33	Poor environment	Poor, dispersed and hostile environment is reorganized.
EPC34	Mental workload	The engineer is changed for inspection duty due to mental workload of the responsible one.

Table 4.11 shows the new results for the new operational conditions. According to these findings, there is no additional countermeasures are required for operational safety of diesel generator overhauling tasks of this case. However, further suggestions should be made for the company's similar operations which can be executed in the future.

Table 4.11 : HEP scales after recovery actions.

Task Class	HEP Scale
2	Very Low
6	Low
7	Very Low
8	Very Low
10	Low
11	Very Low

Overall safety level can be increased limitedly without the integration of innovative upgrades. Hence, newly developed technological units should be adopted to the engine room as soon as possible. For instance, smart sensors for monitoring conditions of machinery systems can provide more effective condition monitoring and additional inspections. These sensors often not require a data transmitter, as they are capable of doing this function too. Moreover, they can receive, transmit, elaborate data and pass commands via digital channels (Ye et al, 2015). In this regard, RFID technology can be utilized as it is one of the most widely used tools for such duties. It can support data exchange and also data storage automatically in a given local area (Chiou & Chang, 2018). By means of these advancements, the state of the system is monitored by approved staff, even if they are not in their office or work area through digital devices and a coordinated network between humans and machines (Campos et al, 2009; Kandemir and Celik, 2017a). Furthermore, a cloud based data storage system can be developed to manage the accumulated data of the entire map. Technological tools such as AR, VR and integrated mobile devices and tablets are supportive tools which enable manage and monitor maintainability of a machinery (Masoni et al, 2017; Caputo et al, 2018; Kandemir and Celik, 2017a). Therefore, 3D virtual scenarios enable operators to conduct maintenance tasks in a virtual environment before carrying them out in real life (Caputo et al, 2018).

The suggestions which can be taken into account are listed below:

- Smart sensors, which enable dynamic condition monitoring, interpreting and transmitting the obtained data and transfer it to the storage.
- Cloud based data storage system to gather and distribute the data in order to provide effective maintenance management.
- Mobile tablets for each operator to read data embedded in the cloud base.
- AR and VR devices which make enable to reach online technical manuals, visual guidance for maintenance tasks and provide virtual environment to simulate an operation before actually doing it.

Due to the potential benefits of these suggestions over maintenance tasks, some of the EPCs can be easily eliminated. This also contributes to the operators' cognition, perception and situational awareness towards potential failures. For example, *EPC17*-namely *inadequate checking*-is removed as operators have the ability to access comprehensive information about their tasks through data storage in their tablets, AR devices or VR devices. Some of EPC may not be entirely eliminated but converted into a different shape. For certain activity tasks, *EPC14 (Objectives conflict)* can be translated into *EPC6 (model mismatch)*. That's because, by technological items, objective conflict is removed, while a model mismatch problem may occur as a software ambiguity (or software error, coding error, or inadequate software design) for a given task. However, it is impossible to eliminate or mitigate some EPCs, such as *EPC34 (Low mental workload)*. These advancements may also reduce the sophistication of the tasks that are related to GEP values. Task complexity can be minimized by means of a smooth condition control program and other resources as the overall intellect of the operator increases.

5. CONCLUSION

The EPCs are the key parameters of the human error probability calculations along with the GTTs. Since the operating conditions of different workplaces will vary from one another, the values of EPC in the traditional HEART should be modified simultaneously. In this regard, some domains such as road transportation, nuclear plants, and railroads have already identified industry specific EPC values. In maritime, the SOHRA approach has been proposed by Akyuz et al. (2016) in order to estimate HEP values for on-board ship operations. This approach has been utilized in many HRA studies in maritime sector, however; since there are two substantially different working divisions on-board as “bridge crew” and “engine room crew”, a further extension of SOHRA was required for HRA of engine room crew. The major difference on the job descriptions is an evidence that confirms this statement. Moreover, maintenance and operations in the engine room require high level of human labour, thus an engine room focused special HRA was needed. In this sense, a research for marine engineering maintenance and operations specific HRA, namely; MMOHRA was initiated.

In order to establish a strong HRA method for a specific domain, human error based causes of past accidents should be analysed meticulously. In this way, a method which provides highly consistent and more accurate estimation of human error likelihood can be proposed. For this reason, past ship accidents arisen from the human error as a result of engine room crew based mistakes were examined. An amount of 1380 ship accidents that occurred between 2008-2018 were thoroughly investigated. There are three important criteria have been considered to filter accident investigation reports when establishing the database of the study; i) Recency of accidents, ii) Reliability of data in the investigation reports, iii) If the responsibility belongs to engine crew or not. In conclusion, 70 marine engineering accident reports that occurred between 2008-2018 has been selected from 12 different accident investigation organisations. Besides, 435 accident causes were identified from these 70 accident reports.

In the process, the original HFACS was planned for classifying 435 causes regarding human factor types, however; a modification for HFACS was required to contribute in attempt to provide more accurate values in MMOHRA. Hence, marine maintenance and operations based human error classification system is proposed as HFACS-MMO. This modification has been carried out by considering the findings derived from the accident reports. In addition to this, some HFACS modification research that have been conducted in maritime domain such as passenger vessels, ice ships, collisions have been taken into account. Since marine maintenance and operations based HFACS has not been studied before, this gap within the literature has been remedied by the HFACS-MMO. Therefore, further studies which belong to human factor analysis applications in marine engineering can take advantage of it.

After the successful design of HFACS-MMO, 435 causes were distributed to the relevant layers and sub-layers of HFACS-MMO. In addition, they have been examined in four different cathegories with respect to their role leading to an accident. This process was done by the AHP which as a MCDM method. All causes in the cathegories were multiplied their AHP based weights to reveal their actual ratings. According to this, the most frequent human factor has been sourced by "*inadequate supervision*" as involving around 11% of all causes. "*Organisational climate*" and "*organisational process*" comes second and third respectively by around 8.7% and 7.8%. "*Skill-based errors*" also very close these ratings by 7.5%. These are the most influencial aspects that leads safety issues in the engine room.

The transformation phase of the HFACS-MMO to mmo-EPCs have been carried out via studiously prepared correlation matrix. Hereby, descriptions of all EPCs were adopted to marine engineering domain. Then, sub-layers of HFACS-MMO were matched with the proper mmo-EPCs. The values of sub-layers were summed for each EPC and then normalized. After the normalization, mmo-EPCs were identified to be utilized in MMOHRA. The processes have been made so far have been initiated once again. This time, the objective was to eliminate judgmental errors which can made by the experts in MCDM methods. In addition to this, the verification of obtained values were intended to be verified. The verification phase was done between the first results and the last ones by independent t-test technique. Eventually, the two-tailed value within this technique has been found as 0.951, which should be higher than 0.05. Hence, the results were verified and there was no need to carry out another round to reach consistent values.

Similar with the other domain specific HRA approaches, newly found mmo-EPCs are the most critical part of MMOHRA. Apart from this difference, the calculation phase is very similar with the SOHRA. However; safety experts have been consuming plenty of time when considering the EPCs and GTTs. In order to achieve this challenge, a rule-based practical calculation tool for MMOHRA was proposed. The rule base for GTT was intended via establishing a matrix which built upon 4 critical aspects (task complexity, task pace, unfamilliarity, operational support & aid). So, the system assignes GTTs depending on the existing aspects via input of the experts. The rule base of EPC has been structured on a matrix which matches task types and potentially affecting EPCs. Therefore, the system asks to the expert for existing EPCs only for one time and then automatically distributes them according to the task types. The coding of this tool was successfully completed via Python 3 language. Besides, SQLite library and database engine was embedded to create GTT and EPC tables of MMOHRA. Consequently, this tool can be employed as an initial safety analysis when there is time constraint to make a comprehensive safety research in marine maintenance and operations.

Since the proposed mmo-EPCs based upon the engine room related data, these values can be used in marine engineering maintenance and operations notwithstanding the ship types. Moreover, because the operational activities in engine rooms are very similar, mmo-EPC values can provide more efficient and reliable human reliability analysis for various types of platforms, including special ships, FPSO ships, platform support vessels, oil rigs and offshore platforms.

To prove these statements, three case studies have been executed under relevant sections of this study. Therefore, some comparisons have been made and the results were discussed. The first study was to calculate HEP values of a three-rotor screw pump overhaul operation. The results were obtained as 53.5% for SOHRA and 31% for MMOHRA. The difference between these two methods can be considered as accuracy difference towards a marine engineering operation.

The second case study was implemented in five different ships in order to have broad idea about good practice tool of MMOHRA. The HFO purifier overhauling can be considered as more complex job in comparison to the screw pump overhaul; as this process consists of 37 sub-steps. This time, rule based calculation tool is utilized and compared with the classical application of MMOHRA. Since the ships have different conditions, the results were varied. However, the overall HEP values of the ships were not so different between these two approaches. Even so, there is a difference is observed in one ship's final HEP values. This means that the good practice tool is open for development. In general, there is a considerably high correlation have found between HEP values. Besides, this case showed that the experts' time consumption during the analysis can reduce between 30% to 58%, according to the circumstances.

The third case study was conducted through a comprehensive diesel generator overhaul operation which consists of 52 sub-tasks. Herein, the MMOHRA approach was fully implemented with rule based tool. This time, recovery actions are undertaken and new conditions were re-calculated until the operational safety comes at satisfying level. The results show that technological devices could have huge potential to increase operational safety in marine maintenance and operations. For this reason, adopting newly intended technological instruments in conjunction with the most proper safety oriented techniques are strongly adviced for responsible ship owners.

Ultimately, this study has been achieved its main objective as well as contributed to the literature as proposing a rule-based HRA to enhance ship auxialliary machinery maintenance operations. The highlights of this research can be listed followingly:

- Marine engineering based accidents were investigated and their causes were identified comprehensively.
- The HFACS-MMO has been proposed as a human factor classification method to be utilized in marine engineering maintenance and operations by adopting the conventional HFACS.
- The mmo-EPCs have been determined in terms of both new descriptions and marine engineering specific values.
- The MMOHRA has been introduced as an extension of SOHRA for marine engineering maintenance and operations.
- The MMOHRA has been successfully implemented to three different auxiliary machineries of several ships. Thus, case specific EPCs have been identified for different ships. Moreover, recovery actions have been suggested to support safety level of a specific case.
- Rule based structure for GTT has been established after meticulous examination of the original descriptions within the HEART method. This

matrix can be utilized in any HRA study notwithstanding the type of the domain or the sector.

- Rule based structure for EPC has been presented via expert judgments by creating a task types-EPC matrix. It can be used for marine maintenance and operations by the relevant safety practitioners.
- A good practice tool of MMOHRA has been intended through combining the established rule based structures of GTT and EPC. Therefore, easy implementation of MMOHRA can be an incentive influence on performing more HRA prior to an operation due to elimination of non-critical tasks which have low HEP values.

Nevertheless, there are also some limitations of the study during its maturation. It is very challenging and mostly unknown to obtain technical or operational data regarding the characteristics of the marine engineering field. For this reason, some of the critical phases of the study depends on the expert judgment. However, finding available experts has taken plenty of time. In addition, their MCDM processes have also lasted long. Even so, the required data have been obtained and the whole MCDM process has been repeated in order to minimize judgmental errors. Even tough, the expert judgment can be relatively subjective data despite the sufficient experiences of decision makers.

In HRA studies, establishing a database is big challenge due to scant data. Hence, this part of the research is achieved with the data that derived from the historical ship accident investigation reports. The surveying of reliable, up to date and marine engineering based accidents have taken very long time. In conclusion, only around 5% of the reviewed reports have taken into account. The derivation of accident causes from the reports have lasted longer than expected in order to grasp the course of events comprehensively. These meticulously derived, classified and calculated real accident data makes MMOHRA a reliable model for the marine engineering literature. Nonetheless, the proposed method can be evaluated through the studies which will be conducted in the future.

For further studies, the ship accident database can be expanded and enrichened with the most recent marine engineering investigation reports. Therefore, mmo-EPCs can be updated in certain time intervals. In addition, the GTTs and corresponding GEP values can be transformed into marine engineering specific parameters. Since the MMOHRA has practical application tool, it can be widely implemented in several different ship auxiliary machinery in various particulars of marine engineering domain. Moreover, the coding of the practical tool can be updated depending on the new requirements of certain operational conditions or the requirements of technology oriented methods such as maintenance 4.0, e-maintenance, machine learning, etc. In this way, the mmo-EPC and GTT assignment processes can be performed more automatically and the time consumption of applications can be reduced significantly.

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APPENDICES

APPENDIX A: Figures.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
HFACS MMO Codes	Unfamilliarity	Time Shortage	Low signal noise ratio	Inadequate instructions	Unreliable instructions	Poor SER Design	Task Irreversibility	Information overload	Opposing philosophy	Knowledge transfer	Ambiguity in	Misperception of Risk	Poor Recording	Poor System Feedback	New or Inexperienced	Poor Information	Inadequate inspection	Long & Short Term	Insufficient Data Variety	Educational Mismatch	Dangerous Procedures	Lack of body & mind	Inadequate Tools & Spare	Absolute Judgment	Poor Responsibility	No Progress Monitoring	Physical Capabilities	Lack of Given	Emotional Stress	Ill-health	Low Workforce Morale	Inconsistent Drawings &	Poor Environment	Low Mental Workload	Irregular work-sleep cycle	Intervention of Task	Abnormal Number of	Improper Age for
1a		x					x											x						x														
1b	x			x	x																		x									x						
1c						x											x				x												x					
2a											x				x				x	x			x			x												
2b													x	x		x					x	x						x			x					x	x	
2c		x		x			x				x						x									x												
2d		x	x				x									x							x		x								x					
3a								x		x			x				x			x				x														
3b		x																x			x				x										x		x	
3c												x						x										x				x						
3d	x												x								x																	
4a												x			x												x		x	x	x			x	x			x
4b					x	x																											x					
4c			x																x							x												
4d													x		x	x						x			x											x	x	
5a	x								x	x					x																							x
5b				x	x		x																	x														
5c	x							x	x	x		x																										
5d				x	x								x																					x				
5e	x		x											x			x				x																	

Figure A.1 : HFACS-EPC matrix.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
	Unfamilliarity	Time Shortage	Low signal noise ratio	Inadequate instructions	Unreliable instructions	Poor SER Design	Task Irreversibility	Information overload	Opposing philosophy required	Knowledge transfer required	Ambiguity in Performance	Misperception of Risk	Poor Recording	Poor System Feedback	New or Inexperienced	Poor Information Transfer	Inadequate inspection	Long & Short Term Objectives	Insufficient Data Variety	Educational Mismatch	Dangerous Procedures	Lack of body & mind exercise	Inadequate Tools & Spare	Absolute Judgment Required	Poor Responsibility	No Progress Monitoring	Physical Capabilities	Lack of Given Importance	Emotional Stress	Ill-health	Low Workforce Morale	Inconsistent Drawings &	Poor Environment	Low Mental Workload	Irregular work-sleep cycle	Intervention of Task Progress	Abnormal Number of	Improper Age for Perceptual
Lifting of Coverings & Blocks					X																		X					X					X					
Disassemmbly of the Equipment				X	X								X										X										X					
Equipment Transfer		X											X			X							X				X					X				X		
Equipment Allignment		X											X										X					X		X		X			X			X
Measurement											X		X	X			X		X				X	X				X	X					X	X			X
Equipment cleaning																						X	X					X		X	X		X					X
Inspection	X	X				X							X	X			X		X				X	X		X		X										
Repair & Replacement	X	X					X						X		X						X		X					X				X						X
Assembly of the Equipment		X		X	X								X										X									X						
Test & Control		X	X				X						X	X			X	X	X		X		X	X		X		X			X	X		X				
Lifting of Coverings & Blocks		X		X	X	X						X			X						X	X	X	X			X	X		X	X		X					X
Disassemmbly of the Equipment				X	X								X								X		X				X					X	X			X		
Equipment Transfer		X		X	X							X	X		X	X					X	X	X		X		X	X		X		X	X			X		
Equipment Allignment	X	X		X	X			X				X	X		X					X			X	X				X	X	X	X	X	X	X	X	X		X
Measurement					X						X		X	X	X		X		X				X	X				X	X		X		X	X	X			X
Equipment cleaning		X													X							X	X	X				X		X	X	X	X	X	X	X		X
Inspection	X	X	X			X						X	X	X	X		X		X				X	X		X		X	X	X	X		X	X				
Repair & Replacement	X	X		X	X		X		X				X		X					X	X		X	X			X	X	X	X	X	X	X	X	X	X	X	X
Assembly of the Equipment	X	X		X	X					X			X		X		X					X	X	X			X	X	X		X	X	X	X	X			X
Test & Control		X	X				X						X	X			X	X	X		X		X	X		X		X			X	X	X	X	X	X		X

Figure A.2 : Task types-EPC matrix.

APPENDIX B : Code in the practical MMOHRA tool

```
import os
import sqlite3

db = sqlite3.connect("mmohra.sql")
cs = db.cursor()
##################################

epcs = dict()
for i in range(39):
    epcs[i] = 0

def addepc():
    epcNo = int(input("EPC No: "))
    curr = epcs[epcNo]
    b = "SELECT value FROM 'epcval5' as float WHERE epc='EPC{}'".format(epcNo)
    cs.execute(b)
    epcv = cs.fetchone()
    res = float('.'.join(str(ele) for ele in epcv))
    addition = res
    total = curr + addition
    epcs[epcNo] = total

def remepc():
    epcNo = int(input("EPC No: "))
    curr = epcs[epcNo]
    b = "SELECT value FROM 'epcval5' as float WHERE epc='EPC{}'".format(epcNo)
    cs.execute(b)
    epcv = cs.fetchone()
    res = float('.'.join(str(ele) for ele in epcv))
    removing = res
    total = curr - removing
    if total < 0:
        print("Please review your decision. There is no such EPC")
    else:
        epcs[epcNo] = total


def filecontrol(file_name):
    try:
        file = open("epcs.txt")
        data = file.read()
        data = data.split("\n")
        data.pop()
        file.close()
        flag = True
    except FileNotFoundError:
        file = open("epcs.txt", "w")
        file.close()
        print("File created")
        flag = False


def updaterec():
    file = open("epcs.txt", "w")
    for i in range(1, 39):
        vs = epcs[i]
        vs = str(vs)
        file.write(vs + "\n")

    file.close()


tasks = dict()
for j in range(12):
    tasks[j] = 0

def addgtt():
    taskNo = int(input("Task No: "))
    curr = tasks[taskNo]
    unfamilliarity = input("Does Unfamilliarity exist for this task? Y or N: ")
    complexity = input("Is the task is complex? Y or N: ")
    rapidity = input("The task must be performed rapidly? Y or N: ")
    nosupporting = input("Information support for this task doesn't exist? Y or N: ")

    if unfamilliarity == "y" and complexity == "y" and rapidity == "y" and nosupporting == "y":
```

```
        x = "A"
    elif unfamilliarity == "y" and complexity == "y" and rapidity == "y" and nosupporting == "n":
        x = "A"
    elif unfamilliarity == "n" and complexity == "y" and rapidity == "y" and nosupporting == "y":
        x = "B"
    elif unfamilliarity == "y" and complexity == "n" and rapidity == "y" and nosupporting == "y":
        x = "B"
    elif unfamilliarity == "y" and complexity == "y" and rapidity == "n" and nosupporting == "y":
        x = "B"
    elif unfamilliarity == "y" and complexity == "y" and rapidity == "n" and nosupporting == "n":
        x = "C"
    elif unfamilliarity == "n" and complexity == "y" and rapidity == "n" and nosupporting == "y":
        x = "C"
    elif unfamilliarity == "y" and complexity == "n" and rapidity == "y" and nosupporting == "n":
        x = "D"
    elif unfamilliarity == "n" and complexity == "n" and rapidity == "y" and nosupporting == "y":
        x = "D"
    elif unfamilliarity == "y" and complexity == "n" and rapidity == "n" and nosupporting == "y":
        x = "E"
    elif unfamilliarity == "y" and complexity == "n" and rapidity == "n" and nosupporting == "n":
        x = "E"
    elif unfamilliarity == "n" and complexity == "y" and rapidity == "y" and nosupporting == "n":
        x = "F"
    elif unfamilliarity == "n" and complexity == "y" and rapidity == "n" and nosupporting == "n":
        x = "F"
    elif unfamilliarity == "n" and complexity == "n" and rapidity == "y" and nosupporting == "n":
        x = "G"
    elif unfamilliarity == "n" and complexity == "n" and rapidity == "n" and nosupporting == "y":
        x = "G"
    elif unfamilliarity == "n" and complexity == "n" and rapidity == "n" and nosupporting == "n":
        x = "H"
    else:
        print("You pressed a wrong button. Please try again...")
        input()

    c = "SELECT value FROM 'gttval' as float WHERE gtt='{}'".format(x)
    cs.execute(c)
    gttv = cs.fetchone()
    resg = float('.'.join(str(ele) for ele in gttv))
    addition = resg
    total = curr + addition
    tasks[taskNo] = total

def remgtt():
    taskNo = int(input("Task No: "))
    tasks[taskNo] = 0.0

def filecontrolgtt(file_name):
    try:
        file = open("gtts.txt")
        data = file.read()
        data = data.split("\n")
        data.pop()
        file.close()
        flag = True
    except FileNotFoundError:
        file = open("gtts.txt", "w")
        file.close()
        print("Dosya oluşturuldu")
        flag = False

def updategttrec():
    file = open("gtts.txt", "w")
    for i in range(1, 12):
        vs = tasks[i]
        vs = str(vs)
        file.write(vs + "\n")

    file.close()
########################################################################

def calculate():
    file = open("epcs.txt", "r")
    data = file.read()
    data = data.split("\n")
    data.pop()

    a = list(epcs.values())
    b = [n for n in a if n > 0]

    file = open("gtts.txt", "r")
    data = file.read()
    data = data.split("\n")
    data.pop()

    p1 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC5' OR epc='EPC23' OR epc='EPC28' OR
epc='EPC33'"
    cs.execute(p1)
```

```
    q1 = cs.fetchall()
    h1 = [item[0] for item in q1]

    epct1 = list(set(b).intersection(set(h1)))
    lengtha = len(epct1)

    p2 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC5' OR epc='EPC4' OR epc='EPC13' OR
epc='EPC23' " \
        "OR epc='EPC33'"
    cs.execute(p2)
    q2 = cs.fetchall()
    h2 = [item[0] for item in q2]

    epct2 = list(set(b).intersection(set(h2)))
    lengthb = len(epct2)

    p3 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC7' OR epc='EPC12' OR epc='EPC13' OR
epc='EPC17' " \
        "OR epc='EPC26'"
    cs.execute(p3)
    q3 = cs.fetchall()
    h3 = [item[0] for item in q3]

    epct3 = list(set(b).intersection(set(h3)))
    lengthc = len(epct3)

    p4 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC2' OR epc='EPC13' OR epc='EPC16' OR
epc='EPC23' " \
        "OR epc='EPC27' OR epc='EPC32'"
    cs.execute(p4)
    q4 = cs.fetchall()
    h4 = [item[0] for item in q4]

    epct4 = list(set(b).intersection(set(h4)))
    lengthd = len(epct4)

    p5 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC2' OR epc='EPC13' OR epc='EPC28' OR
epc='EPC23' " \
        "OR epc='EPC30' OR epc='EPC32' OR epc='EPC35' OR epc='EPC38'"
    cs.execute(p5)
    q5 = cs.fetchall()
    h5 = [item[0] for item in q5]

    epct5 = list(set(b).intersection(set(h5)))
    lengthe = len(epct5)

    p6 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC11' OR epc='EPC13' OR epc='EPC14' OR
epc='EPC17' " \
        "OR epc='EPC19' OR epc='EPC23' OR epc='EPC24' OR epc='EPC28' OR epc='EPC29' OR
epc='EPC34' OR epc='EPC35' " \
        "OR epc='EPC38'"
    cs.execute(p6)
    q6 = cs.fetchall()
    h6 = [item[0] for item in q6]

    epct6 = list(set(b).intersection(set(h6)))
    lengthf = len(epct6)

    p7 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC22' OR epc='EPC31' OR epc='EPC28' OR
epc='EPC23' " \
        "OR epc='EPC30' OR epc='EPC33' OR epc='EPC38'"
    cs.execute(p7)
    q7 = cs.fetchall()
    h7 = [item[0] for item in q7]

    epct7 = list(set(b).intersection(set(h7)))
    lengthg = len(epct7)

    p8 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC1' OR epc='EPC2' OR epc='EPC6' OR
epc='EPC13' " \
        "OR epc='EPC14' OR epc='EPC17' OR epc='EPC19' OR epc='EPC23' OR epc='EPC24' OR
epc='EPC26' OR epc='EPC28'"
    cs.execute(p8)
    q8 = cs.fetchall()
    h8 = [item[0] for item in q8]

    epct8 = list(set(b).intersection(set(h8)))
    lengthh = len(epct8)

    p9 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC1' OR epc='EPC2' OR epc='EPC7' OR
epc='EPC13' " \
        "OR epc='EPC15' OR epc='EPC21' OR epc='EPC23' OR epc='EPC32' OR epc='EPC38'"
    cs.execute(p9)
    q9 = cs.fetchall()
    h9 = [item[0] for item in q9]

    epct9 = list(set(b).intersection(set(h9)))
    lengthi = len(epct9)
```

```
    p10 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC2' OR epc='EPC4' OR epc='EPC5' OR
epc='EPC13' " \
          "OR epc='EPC23' OR epc='EPC32'"
    cs.execute(p10)
    q10 = cs.fetchall()
    h10 = [item[0] for item in q10]

    epct10 = list(set(b).intersection(set(h10)))
    lengthj = len(epct10)

    p11 = "SELECT value FROM 'epcval5' as float WHERE epc='EPC2' OR epc='EPC3' OR epc='EPC7' OR
epc='EPC13' " \
          "OR epc='EPC14' OR epc='EPC17' OR epc='EPC18' OR epc='EPC19' OR epc='EPC21' OR
epc='EPC23'" \
          "OR epc='EPC24' OR epc='EPC26' OR epc='EPC28' OR epc='EPC31' OR epc='EPC32' OR
epc='EPC34'"

    cs.execute(p11)
    q11 = cs.fetchall()
    h11 = [item[0] for item in q11]

    epct11 = list(set(b).intersection(set(h11)))
    lengthk = len(epct11)

    for i in range(1, 12):
        gttt1 = tasks.get(i)

        if i == 1:
            gttta = gttt1
            length = lengtha

        elif i == 2:
            gtttb = gttt1
            length = lengthb
            epct1=epct2

        elif i == 3:
            gtttc = gttt1
            length = lengthc
            epct1 = epct3

        elif i == 4:
            gtttd = gttt1
            length = lengthd
            epct1 = epct4

        elif i == 5:
            gttte = gttt1
            length = lengthe
            epct1 = epct5

        elif i == 6:
            gtttf = gttt1
            length = lengthf
            epct1 = epct6

        elif i == 7:
            gtttg = gttt1
            length = lengthg
            epct1 = epct7

        elif i == 8:
            gttth = gttt1
            length = lengthh
            epct1 = epct8

        elif i == 9:
            gttti = gttt1
            length = lengthi
            epct1 = epct9

        elif i == 10:
            gtttj = gttt1
            length = lengthj
            epct1 = epct10

        elif i == 11:
            gtttk = gttt1
            length = lengthk
            epct1 = epct11

        else:
            pass

        if gttt1 > 0:
            if length == 0:
                hep1 = 0
```

```
                print("For Task {}  HEP= No probability".format(i, hep1))
            elif length == 1:
                hep1 = epct1[0] * gttt1
                if hep1==0:
                    print("For Task {} HEP= No Probability".format(i, hep1))
                elif hep1<= 0.05:
                    print("For Task {} HEP= Very Low".format(i, hep1))
                elif hep1<= 0.15:
                    print("For Task {} HEP= Low".format(i, hep1))
                elif hep1<= 0.25:
                    print("For Task {} HEP= Medium".format(i, hep1))
                elif hep1<= 0.5:
                    print("For Task {} HEP= High!".format(i, hep1))
                elif hep1>= 0.05:
                    print("For Task {} HEP= Very High!!!".format(i, hep1))
            elif length == 2:
                hep1 = gttt1 * ((epct1[0] - 1) * 0.5 + 1) * ((epct1[1] - 1) * 0.5 +1)
                if hep1==0:
                    print("For Task {} HEP= No Probability".format(i, hep1))
                elif hep1<= 0.05:
                    print("For Task {} HEP= Very Low".format(i, hep1))
                elif hep1<= 0.15:
                    print("For Task {} HEP= Low".format(i, hep1))
                elif hep1<= 0.25:
                    print("For Task {} HEP= Medium".format(i, hep1))
                elif hep1<= 0.5:
                    print("For Task {} HEP= High!".format(i, hep1))
                elif hep1>= 0.05:
                    print("For Task {} HEP= Very High!!!".format(i, hep1))
            elif length == 3:
                hep1 = gttt1 * ((epct1[0] - 1) * 0.333 + 1) * ((epct1[1] -1) *0.333+  1) * (
                            (epct1[2] - 1) * 0.333 + 1)
                if hep1==0:
                    print("For Task {} HEP= No Probability".format(i, hep1))
                elif hep1<= 0.05:
                    print("For Task {} HEP= Very Low".format(i, hep1))
                elif hep1<= 0.15:
                    print("For Task {} HEP= Low".format(i, hep1))
                elif hep1<= 0.25:
                    print("For Task {} HEP= Medium".format(i, hep1))
                elif hep1<= 0.5:
                    print("For Task {} HEP= High!".format(i, hep1))
                elif hep1>= 0.05:
                    print("For Task {} HEP= Very High!!!".format(i, hep1))
            elif length == 4:
                hep1 = gttt1 * ((epct1[0] - 1) * 0.25 + 1) * ((epct1[1] - 1) * 0.25 + 1) * (
                            (epct1[2] - 1) * 0.25 + 1) * ((epct1[3] - 1) * 0.25 + 1)
                if hep1==0:
                    print("For Task {} HEP= No Probability".format(i, hep1))
                elif hep1<= 0.05:
                    print("For Task {} HEP= Very Low".format(i, hep1))
                elif hep1<= 0.15:
                    print("For Task {} HEP= Low".format(i, hep1))
                elif hep1<= 0.25:
                    print("For Task {} HEP= Medium".format(i, hep1))
                elif hep1<= 0.5:
                    print("For Task {} HEP= High!".format(i, hep1))
                elif hep1>= 0.05:
                    print("For Task {} HEP= Very High!!!".format(i, hep1))
            elif length == 5:
                hep1 = gttt1 * ((epct1[0] - 1) * 0.2 + 1) * ((epct1[1] - 1) * 0.2 + 1) * (
                            (epct1[2] - 1) * 0.2 + 1) * ((epct1[3] - 1) * 0.2 + 1)*((epct1[4] -
1) * 0.2 + 1)
                if hep1==0:
                    print("For Task {} HEP= No Probability".format(i, hep1))
                elif hep1<= 0.05:
                    print("For Task {} HEP= Very Low".format(i, hep1))
                elif hep1<= 0.15:
                    print("For Task {} HEP= Low".format(i, hep1))
                elif hep1<= 0.25:
                    print("For Task {} HEP= Medium".format(i, hep1))
                elif hep1<= 0.5:
                    print("For Task {} HEP= High!".format(i, hep1))
                elif hep1>= 0.05:
                    print("For Task {} HEP= Very High!!!".format(i, hep1))
            elif length == 6:
                hep1 = gttt1 * ((epct1[0] - 1) * 0.166 + 1) * ((epct1[1] - 1) * 0.166 + 1) * (
                            (epct1[2] - 1) * 0.166 + 1) * ((epct1[3] - 1) * 0.166 + 1)*((epct1[4]
- 1) * 0.166 + 1)*((epct1[5] - 1) * 0.166 + 1)
                if hep1==0:
                    print("For Task {} HEP= No Probability".format(i, hep1))
                elif hep1<= 0.05:
                    print("For Task {} HEP= Very Low".format(i, hep1))
                elif hep1<= 0.15:
                    print("For Task {} HEP= Low".format(i, hep1))
                elif hep1<= 0.25:
                    print("For Task {} HEP= Medium".format(i, hep1))
                elif hep1<= 0.5:
```

```
                print("For Task {} HEP= High!".format(i, hep1))
            elif hep1>= 0.05:
                print("For Task {} HEP= Very High!!!".format(i, hep1))
        elif length == 7:
            hep1 = gttt1 * ((epct1[0] - 1) * 0.143 + 1) * ((epct1[1] - 1) * 0.143 + 1) * (
                        (epct1[2] - 1) * 0.143 + 1) * ((epct1[3] - 1) * 0.143 + 1)*((epct1[4]
- 1) * 0.143 + 1)*((epct1[5] - 1) * 0.143 + 1)*((epct1[6] - 1) * 0.143 + 1)
            if hep1==0:
                print("For Task {} HEP= No Probability".format(i, hep1))
            elif hep1<= 0.05:
                print("For Task {} HEP= Very Low".format(i, hep1))
            elif hep1<= 0.15:
                print("For Task {} HEP= Low".format(i, hep1))
            elif hep1<= 0.25:
                print("For Task {} HEP= Medium".format(i, hep1))
            elif hep1<= 0.5:
                print("For Task {} HEP= High!".format(i, hep1))
            elif hep1>= 0.05:
                print("For Task {} HEP= Very High!!!".format(i, hep1))
    else:
        hep1 = 0
        print("For Task {} HEP= No Probability".format(i, hep1))

    print()
    file.close()
    input()
###################################################################

def main():
    filecontrol("epcs.txt")
    filecontrolgtt("gtts.txt")
    while True:
        os.system("cls")
        print("""
        Welcome to MMOHRA Practical Calculation Tool

        [1] Enter GTTs
        [2] Enter EPCs
        [3] View Existing GTTs
        [4] View Existing EPCs
        [5] Remove GTT
        [6] Remove EPC
        [7] Calculate
        [Q] Exit

        GTT: General Task Type
        EPC: Error Producing Condition

        """)
        sel = input("Your Choice: ")

        if sel == "1":
            print("""The list of the marine engineering maintenance tasks:

                Task 1 : Lifting of Coverings or Blocks
                Task 2 : Disassembly of equipment
                Task 3 : Drill liquids from equipment
                Task 4 : Equipment Transfer
                Task 5 : Equipment Allignment
                Task 6 : Measurement of Equipment
                Task 7 : Cleaning of Equipment
                Task 8 : Inspection of Equipment
                Task 9 : Replacement, Repair & Maintenance
                Task 10: Assembly of Equipment
                Task 11: Test & Control of Equipment

                Please add a task type from the list.
                Please don't add if a task type doesn't included in your operation.

                  """)
            addgtt()
            print("Selected Task added")
            updategttrec()
            input()

        elif sel == "2":
            addepc()
            print("The EPC was added, press ENTER to proceed...")
            updaterec()
            input()

        elif sel == "3":
            for i in range(1, 12):
                print("For Task {} value is:{}".format(i, tasks[i]))
            print("Press ENTER to proceed")
            input()

        elif sel == "4":
```

```
            for i in range(1, 39):
                print(" For EPC {} the value is: {}".format(i, epcs[i]))
            print("Press ENTER to proceed")
            input()

        elif sel == "5":
            remgtt()
            print("Selected GTT was removed. Press ENTER to proceed")
            updategttrec()
            input()

        elif sel == "6":
            remepc()
            print("Selected EPC was removed. Press ENTER to proceed")
            updaterec()
            input()

        elif sel == "7":
            calculate()
            input()

        elif sel == "Q" or sel == "q":
            print("Escaping...")
            quit()

main()
```

CURRICULUM VITAE

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PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Kandemir, C.,** Celik, M., Akyuz, E., Aydin, O. 2019: Application of human reliability analysis to repair & maintenance operations on-board ships: The case of HFO purifier overhauling. *Applied Ocean Research*, 88, 317-325. (Article Instance)
- **Kandemir, C.,** & Celik, M. 2020: A human reliability assessment of marine auxiliary machinery maintenance operations under ship PMS and maintenance 4.0 concepts. *Cognition, Technology & Work*, 1-15. (Article Instance)

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