ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DEVELOPMENT OF A DYNAMIC NAVIGATIONAL RISK ASSESSMENT MODEL

Ph.D. THESIS

Yunus Emre ŞENOL

Department of Maritime Transportation Engineering

Maritime Transportation Engineering Programme

JUNE 2020

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DEVELOPMENT OF A DYNAMIC NAVIGATIONAL RISK ASSESSMENT MODEL

Ph.D. THESIS

Yunus Emre ŞENOL
(512142005)

Department of Maritime Transportation Engineering

Maritime Transportation Engineering Programme

Thesis Advisor: Prof. Dr. Özcan ARSLAN

JUNE 2020

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

DİNAMİK BİR SEYİR RİSK ANALİZİ MODELİNİN GELİŞTİRİLMESİ

DOKTORA TEZİ

Yunus Emre ŞENOL
(512142005)

Deniz Ulaştırma Mühendisliği Anabilim Dalı

Deniz Ulaştırma Mühendisliği

Tez Danışmanı: Prof. Dr. Özcan ARSLAN

HAZİRAN 2020

Yunus Emre ŞENOL, a Ph.D. student of ITU Graduate School of Science Engineering and Technology student ID 512142005, successfully defended the thesis entitled "DEVELOPMENT OF A DYNAMIC NAVIGATIONAL RISK ASSESSMENT MODEL", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Prof. Dr. Özcan ARSLAN** İstanbul Technical University	....
Jury Members :	**Prof. Dr. Serdar KUM** İstanbul Technical University	....
	Assoc. Prof. Dr. Tanzer SATIR İstanbul Technical University	....
	Assoc. Prof. Dr. Özkan UĞURLU Ordu University	....
	Asst. Prof. Dr. Aydın ŞIHMANTEPE Piri Reis University	....

Teslim Tarihi : 19 Mayıs 2020
Savunma Tarihi : 11 Haziran 2020

To my family,

FOREWORD

I would like to express my extreme gratitude and appreciation to my thesis supervisor, Prof. Dr. Özcan Arslan for his encouragement, unflagging supports and generous guidance. I also would like to express my great gratitude to Assoc. Prof. Dr. Alexandre Tsetskhladze for his hospitality and endless support to my researches in Batumi State Maritime Academy. Their indispensable support in the completion of my thesis will be remembered throughout my academic career and even throughout my life.

I owe a debt of gratitude to Assoc. Prof. Dr. Tanzer Satır and Asst. Prof. Dr. Aydın Şıhmantepe, who are the steering committee members of my thesis, for their gentle routings and helpful recommendations.

I also would like to express my special acknowledgement to TÜBİTAK for the financial support I received from the BİDEB 2211 scholarship program during my PhD education.

May 2020

Yunus Emre ŞENOL
(Lecturer)

TABLE OF CONTENTS

Page

ABBREVIATIONS

1D	: One-dimensional
2D	: Two-dimensional
3D	: Three-dimensional
AIS	: Automatic Identification System
ASCII	: American Standard Code for Information Interchange
AtoN	: Aids to Navigation
BBN	: Bayesian Belief Network
BCR	: Bow Cross Range
BCT	: Bow Cross Time
BE	: Basic Event
BN	: Bayesian Network
BNWAS	: Bridge Navigational Watch Alarm System
BPNN	: Back Propagation Neural Network
CAN	: Controller Area Network
CNB	: Common Navigation Block
COG	: Course Over Ground
COLREG	: International Regulations for Preventing Collisions at Sea
CPA	: Closest Point of Approach
CR	: Crossing
CRA	: Convenience for Dynamic Real Time Risk Analysis
DDV	: Degree of Domain Violation
DSC	: Digital Selective Calling
ECDIS	: Electronic Chart and Information System
EMSA	: European Maritime Safety Agency
ENC	: Electronic Navigational Chart
EPIRB	: Emergency Position Indicating Radio Beacon
FIS	: Fuzzy Inference System
FQSD	: Fuzzy Quaternion Ship Domain
FTA	: Fault Tree Analysis
GDAL	: Geospatial Data Abstraction Library
GPS	: Global Positioning System
GT	: Gross Tonnage
HF	: High Frequency
HO	: Head-On
IHO	: International Hydrographic Organization
IMO	: International Maritime Organization
INS	: Integrated Navigation System
LOA	: Length Over All
MDTC	: Minimum Distance to Collision
MF	: Medium Frequency
MGIS	: Marine Geographic Information System
Min	: Minute

MMSI : Maritime Mobile Service Identity
MSOD : Minimum Safe Overtaking Distance
nm : Nautical mile
NMEA : The National Marine Electronics Association
OS : Own Ship
OT : Overtaking
PhD : Doctor of Philosophy
RA : Restricted Area
RAIM : Receiver Autonomous Integrity Monitoring
RC-FFTA : Real-Continuous Fuzzy Fault Tree Analysis
ROT : Rate of Turn
SI : Safety Index
SJ-value : Subjective Judgement value
SOG : Speed Over Ground
SOLAS : International Convention for the Safety of Life at Sea
TCPA : Time to Closest Point of Approach
TDV : Time to Domain Violation
TE : Top Event
TS : Target Ship
UNCTAD : United Nations Conference on Trade and Development
UTC : Coordinated Universal Time
VCD : Variance of Compass Degree
VCRO : Vessel Conflict Ranking Operator
VDR : Voyage Data Recorder
VHF : Very High Frequency
VTS : Vessel Traffic Service

SYMBOLS

!AIVDM	**:** Target ship AIS message ID
!AIVDO	**:** Own ship AIS message ID
$	**:** NMEA 0183 Message Starting Letter
$\mu_A(X)$	**:** Membership function of x in A fuzzy set
A	**:** Fuzzy set
P_{RG}	**:** Real grounding risk
P_G	**:** Geometrical probability
P_{CG}	**:** Causation probability
P_{Coll}	**:** Collision Probability
P_{CC}	**:** Causation Probability
S	**:** Subsets of a Fuzzy Set
S_f	**:** Subset for linguistic variable of fast
S_m	**:** Subset for linguistic variable of medium
S_l	**:** Subset for linguistic variable of low
X	**:** Universe of discourse
x	**:** Element(s) of Universe of discourse

LIST OF TABLES

Page

LIST OF FIGURES

Page

DEVELOPMENT OF A DYNAMIC NAVIGATIONAL RISK ASSESSMENT MODEL

SUMMARY

Marine traffic, which has an increasing importance in terms of global freight and passenger transportation, has increased significantly in recent years and has brought some navigational safety problems. An increase was observed especially in collision and grounding accidents in especially dense waterways. In order to find solutions to this problem, many academic studies have been carried out that offer different sights and analysis methods. In the literature review stage made within the scope of the thesis, the studies on the subject were examined in detail, the factors included to calculations, the methods utilised and their applicability to the solution of the problem were evaluated. Although the studies in the literature constitute an academic value in terms of their proposed methods and approaches, it has been evaluated that many of them are insufficient in terms of applicability, namely the solution of the problem faced by the industry. As a matter of fact, there is no real-time dynamic risk analysis algorithm that can work onboard ship which is capable of corresponding the needs of the industry. In addition, many studies in the literature do not seem to address both the risks of collision and grounding at the same time. Studies in which only collision or grounding risk analysis was presented could not fully meet the expectations of the maritime sector. For this reason, it is aimed to develop a real-time dynamic risk analysis algorithm with some novel and strong aspects which can provide decision support to the officer on watch, can work integrated with real navigational equipment.

The proposed algorithm consists of 4 main stages as Automatic Identification System (AIS) Module where AIS data are decode and parsed, Electronic Navigational Chart (ENC) Module that allows reading ENCs, Calculation Module where all risks and other required calculations are performed, and Visualisation Module where risk indicators are projected with AIS targets over the visualized ENCs. The National Marine Electronics Association (NMEA) 0183 infrastructure, which is the standard data exchange protocol of ship navigation equipment, has been added to the algorithm so that it can be integrated to navigation equipment for real-time calculations. All of the factors obtained from integrated navigation equipment used as data source and which may affect the risk of collision and grounding were included directly or indirectly as inputs. Information of Closest Point of Approach (CPA), Time to Closest Point of Approach (TCPA), relative bearing, relative speed, ship's length and ship's type are determined as the system inputs of the algorithm.

Own ship and target ships perceived with AIS data are not considered as a single point as in the classical approaches in the literature. Instead, the actual dimensions of the ships are calculated by considering the position information of the Global Positioning System (GPS) receiver sent by OTS on the ship. Ship forms created in real dimensions are perceived as a set of multi-points consisting of points in which a distance of less than 10 meters between each one, and risk calculations of collision is carried out in

real time by including all of these points in consideration. Similarly, shallow contour information obtained using ENC, which is dangerous in terms of vessel draft value, is perceived as a set of multi-points with a distance of less than 10 meters between them.

Risk calculations have been conducted with the Fuzzy Inference System (FIS) method, which is widely used as one of artificial intelligence methods, from medicine to many branches of engineering. A case study was carried out by applying the AIS data of a ship navigating in the Istanbul Strait to the model. In this study, it is aimed to develop a model to reduce the risks of collision and grounding by increasing situational awareness and thus providing a decision support.

DİNAMİK BİR SEYİR RİSK ANALİZİ MODELİNİN GELİŞTİRİLMESİ

ÖZET

Küresel yük ve yolcu taşımacılığı bakımından giderek artan bir öneme sahip olan denizcilik taşımacılığında son yıllarda ciddi şekilde artış gösteren deniz trafiği bazı seyir emniyeti problemlerini beraberinde getirmiştir. Özellikle yoğun suyollarında yaşanan çatışma ve karaya oturma kazalarında artış olduğu gözlemlenmiştir. Yaşanan bu problem üzerine çözüm üretmek amacıyla farklı bakış açısı ve analiz yöntemi sunan pek çok akademik çalışma yapılmaktadır. Bu tezde, artan deniz trafiği ve buna bağlı olarak yaşanan karaya oturma ve çatışma risklerinin en aza indirgenerek emniyetli seyrin tesis edilmesi amacıyla yeni ve güçlü yönleri olan bir gerçek zamanlı seyir risk analiz modeli geliştirilmiştir.

Tez kapsamında yapılmış olan literatür taraması aşamasında konu hakkındaki çalışmalar detaylı şekilde incelenmiş, kullanılan faktörler, kullanılan yöntemler ve problemin çözümü açısından uygulanabirlikleri değerlendirilmiştir. Literatürdeki çalışmalar önerdikleri yöntem ve yaklaşımlar açısından akademik anlamda değer teşkil etmesine rağmen pek çoğunun uygulanabilirlik ve dolayısı ile endüstrinin karşılaştığı problemin çözümü noktasında yetersiz kaldığı gözlemlenmiştir. Nitekim endüstrinin ihtiyaçlarına tam manasıyla cevap verebilecek yeterlikte gerçek zamanlı, gemide çalışabilir dinamik risk analiz algoritması çalışmasına rastlanmamıştır. Ayrıca literatürdeki pek çok çalışmanın hem çatışma hem de karaya oturma risklerini aynı anda ele almadığı görülmektedir. Yalnızca çatışma ya da yalnızca karaya oturma risk analizinin sunulduğu çalışmalar deniz taşımacılığı sektörünün beklentilerinin karşılanması konusunda eksik kalabilmektedir. Bu nedenle çalışma kapsamında gemide vardiya zabitine karar desteği sunabilecek, gerçek seyir ekipmanları ile entegre çalışabilen ve akademik yönü güçlü bir çatışma ve karaya oturmaya tehlikelerine yönelik gerçek zamanlı dinamik risk analiz algoritmasının geliştirilmesi hedeflenmiştir. Algoritma, Otomatik Tanımlama Sistemi (OTS) verilerinin çözümlendiği ve tanımlandığı OTS modülü, Elektronik Seyir Haritaları'nın (ESH) okunmasını sağlayan ESH modülü, risk ve elde edilen verilerin oluşturulan risk modeline uygulanabilmesi için gereken diğer tüm hesaplamaların gerçekleştirildiği Hesaplama Modülü ve elde edilen ESH ile OTS verilerinden model kapsamında ihtiyaç duyulan bölümleri ile risk göstergelerini yansıtan kullanıcı arayüzünün oluşturulduğu Görselleştirme Modülü olmak üzere 4 temel modülden oluşmaktadır. Gemi seyrüsefer ekipmanlarının standart veri alış-veriş protokolü olan The National Marine Electronics Association (NMEA) 0183 alt yapısı ile hazırlanan algoritma bu sayede seyir ekipmanlarına entegre edilip çalıştırılabilir hale getirilmiştir. Veri kaynağı olarak kullanılan modern seyrüsefer ekipmanlarından elde edilen ve çatışma ile karaya oturma riskine etki edebilecek faktörlerin tümü hesaplamalara girdi olarak dahil edilmiştir. Risk hesaplamalarına doğrudan girdi olarak dahil edilmeyen pek çok dinamik verinin sistem girdilerinin hesaplanmasında kullanıldığı ve dolaylı olarak risk hesaplamalarına dahil edildiği bir model oluşturulmuştur. En Yakın Yaklaşma Noktası (EYN), En Yakın Yaklaşma Noktası Zamanı (EYNZ), nispi kerteriz, nispi hız, gemi

boyu ve gemi tipi bilgileri algoritmanın sistem girdileri olarak belirlenmiştir. OTS verileri ile algılanan hedef gemiler ve ana gemi literatürdeki klasik yaklaşımlarda olduğu gibi tek nokta olarak değerlendirilmemektedir. Bunun yerine OTS tarafından gönderilen GPS alıcısının gemi üzerindeki konum bilgisi dikkate alınarak gemilerin gerçek boyutları hesaplanmaktadır. Gerçek boyutlarında oluşturulan gemi şekilleri, aralarında 10 metreden daha az mesafe bulunan çoklu noktalar kümesi şeklinde algılanmakta ve risk değerlendirmesi bu noktaların tümünün gerçek zamanlı olarak hesaplamalara dahil edilmesi ile gerçekleştirilmektedir. Böylece gemiler yalnızca GPS alıcısı tarafından üretilen konumda noktasal şekilde değil, denizel çevrede gerçek eni ve boyu ile gerçek gemi şeklinde algılanmaktadır. Bu uygulama hem çatışma hem de karaya oturma risk hesaplamalarında da kullanılmıştır. Karaya oturma risk hesaplamalarının gerçekleştirilebilmesi aşamasında gerekli olan derinlik bilgisi için elektronik seyir haritalarından faydalanılmıştır. Ancak genelde standart olarak 0, 5, 10, 20, 30, 50 metre derinlik konturlarının sunulduğu elektronik seyir haritalarının kullanımı, bu derinliklerden farklı su çekimine sahip bir gemi için tehlike oluşturacak sığlık kontur bilgisinin algılanmasında yetersiz kalmaktadır. Elektronik seyir haritalarının uluslararası standartta gösterimini yaparak kağıt haritaya ihtiyaç olmadan seyir imkanı sağlayan Elektronik Harita Gösterim Sistemi (EHGS) dahi gemi su çekimi değerinin standart kontur listesinde bulunmaması durumunda, bu değere en yakın daha derin konturu sığlık rengi olan koyu mavi ile renklendirmektedir. Ancak geliştirilen algoritma sayesinde gemi için tehlike oluşturacak sığ kontur çizgisi geminin su çekimi değerine en yakın daha derin ve daha sığ kontur bilgilerinin elektronik seyir haritalarından alınarak yüksek dereceli enterpolasyon yöntemi ile gerçek sığ kontur çizgisini oluşturabilmektedir. Oluşturulan sığ kontur çizgisi de aralarında 10 metreden daha az mesafe bulunan çoklu noktalar kümesi olarak algılanarak risk hesaplamalarına dahil edilmektedir.

Risk hesaplamaları tıp alanından mühendisliğin pek çok dalına kadar yaygın bir kullanımı olan ve yapay zeka yöntemlerinden biri olarak sınıflandırılan Bulanık Çıkarım Sistemi (BÇS) yöntemi ile gerçekleştirilmiştir. Bulanıklaştıma, bulanık çıkarım, bilgi tabanı oluşturma ve durulaştırma olarak 4 ana aşamadan oluşmaktadır. Bu yöntem kesin girişlerin bulanıklaştırıldığı, alan uzmanlarının cevaplamaları ile elde edilen kurallar dahilinde çıkarım mekanizmasının çalıştırıldığı ve hesaplanan bulanık sonucun durulaştırıldığı bir sistemdir. Risk hesaplamaları için girdi olarak belirlenen faktörlerin tümü birbirlerine "ve" operatörleriyle bağlanarak "eğer – ise" kuralları ortaya çıkarılmıştır. Hesaplamalarda kullanılan girdiler; Eğer EYN Düşük, ve EYNZ Düşük, ve nispi kerteriz pruvaya Yakın, ve nispi hız Yüksek, ve gemi boyu Büyük, ve gemi tipi Tanker ise çatışma risk sonucu Yüksek örneğinde olduğu gibi girdilerin temsil edildiği tüm dilsel değişkenlere sahip oldukları durumlar için birbirleri ile birleştirilmiştir. Bunun sonucu olarak toplamda karaya oturma riski için 486, çatışma riski için ise 2916 adet girdi kombinasyonu elde edilmiştir. Hazırlanan kuralların risk sonuçlarına bağlanması işlemi için ilgili alan uzmanı 10 kişiden destek alınmıştır. Kural sayılarının cevaplama sürecini olumsuz etkileyebileceği düşüncesi ile dinamik ve statik olarak sınıflandırılan faktörlerin önce kendi içinde birbirleri ile, daha sonra da elde edilen dinamik ve statik çıktıların birbirleri ile ayrı çıkarım mekanizmasına tabi tutulmasına karar verilmiştir. Bu sayede kural sayısı karaya oturma riski için 96, çatışma riski için ise 126 olacak şekilde azaltılmıştır.

Klasik BÇS yaklaşımı uzman görüşlerine dayanarak kural sonuçları ile ilgili fikir birliği oluşturulması esasına göre uygulanmaktadır. Tez kapsamında oluşturulan algoritmada ise danışılan ilgili alan uzmanlarının da kural cevaplamaları ayrı ayrı yapılmış ve birbirinden bağımsız 10 farklı çıkarım süreci yürütülmüştür. Müteakiben elde edilen kesin sonuçlar, danışılan uzmanların önceden belirlenmiş olan kriterlere göre tespit edilen uzmanlık katsayıları oranında toplanarak nihai tek bir risk sonucu hesaplanmıştır. Bu yöntem uygulanarak her bir kural için oluşturulması gereken fikir birliği nedeniyle uzmanların farklı görüşlerinin yansıtılamaması tehdidinin önüne geçilmesi hedeflenmiştir.

Tez kapsamında, İstanbul Boğazı'nda seyreden bir geminin OTS verilerinin modele uygulanması ile oluşturulan gerçek senaryoya ait bir örnek olay incelemesi gerçekleştirilmiştir. Çatışma ve karaya oturma risklerinin çizgi ve pasta grafikleri ile geminin anlık sahip olduğu risk değerine göre gemi izinin renklendirildiği şematik iz ve senaryoya ait ekran görüntüleri sunulmuştur. Algoritma tarafından üretilen bu çıktılar sayesinde bir geminin seyir emniyet performansının detaylı şekilde değerlendirilmesi mümkün hale getirilmiştir.

Gemide gerçek zamanlı seyir risk analizi gerçekleştiren bir modelin önerildiği bu çalışmanın gemi seyir zabitine riskli durumları bildirmesi, riskin kaynağının gösterilmesi özellikleri sayesinde farkındalığını artıracağı ve olası seyir risklerinin henüz oluşum aşamasında azaltılarak daha emniyetli seyrin tesis edilmesine katkı sunacağı değerlendirilmektedir. Ayrıca yoğun suyollarının gözlemlenmesi ve deniz trafiği izlenmesi, gerekli hallerde müdahale ve ön alma amacıyla oluşturulan Gemi Trafik Hizmetler (GTH) operatörler tarafından sunulmaktadır. Yetki alanları dahilinde bulunan tüm gemileri aynı anda maksimum dikkat ve özenle takip etmeleri her zaman mümkün olmayabilmektedir. Önerilen modelin GTH operatörleri için durumsal farkındalığı artırıcı ve iş yüklerini azaltıcı anlamda kullanılmasının da seyir emniyetini tesis edilmesi hususunda önemli bir aksiyon olabileceği değerlendirilmektedir. Buna ek olarak modelin GTH sistemlerine entegre edilmesi ve uzun dönem kullanılması neticesinde ortaya çıkacak olan istatistiki bilgiler ışığında belirli bölgeler için azami sürat, gemiler arası minimum mesafe, izlenecek emniyetli rotalar gibi emniyet tavsiyelerinin oluşturulması ya da emniyet tedbirleri alınması hususuna da katkı sunacağı değerlendirilmektedir.

1. INTRODUCTION

1.1 Background and Motivation

Marine transportation has an important role for worldwide trade and economics as almost 90% of all kind of commodities are carried through waterborne carriage (UNCTAD, 2017). In many waterways including bays, ports and inland waters, marine traffic has been increasing drastically (2010; 2014) which brings about marine casualties that usually ends up with fatalities, injuries, ship loss and pollution events. 28,655 ship involved accidents and incidents have been recorded between 2011 and 2016 (EMSA, 2017a). 3,296 accidents and incidents have been recorded in 2015. %50 of these casualties were of collision, grounding or contact (EMSA, 2017b).

Navigational safety is a key element of maritime transportation and thus there exist continuously amendments and upgrades to constitute a safer worldwide navigation. With the development of technology, new technological facilities emerged and came into operation on board ships that includes provision of more precise ship identification, safer route planning, automated control systems and advanced navigational aids. Despite improvements on navigational systems, number of collision and grounding casualties cannot be reduced significantly (Chen et al., 2014). Many academic researches and non-commercial studies indicates that navigational safety is directly related to human factor. According to European Maritime Safety Agency's (EMSA) annual report (EMSA, 2017b), human factor has the most significant contribution to reported accidents by %77. Gale et al. (2007) pointed out human factor has an impact on marine casualties by %60 (Gale & Patraiko, 2007). They also stated the effects of insufficient assessment of situation by %24 and poor look out by %23. Thus safety of navigation is understandably related to situational awareness of watch officers. Accordingly, there is a strong demand to a real-time risk indicating system on board which is able to support an augmented situational awareness. This need can only be met by models that can offer a proactive approach to the calculation of navigational risks. The vast majority of current studies are based on historical data obtained from marine accidents, which can only be described as a reactive approach. Unlike the previous ones, this thesis proposes a model for determination of navigation risks with a proactive approach that does not need pre-rehabilitated data and is ready for use on ships. Significant approaches and evaluation methods were published in the literature, to enhance safety of navigation by analysing navigational risks. They could be classified as; analytical, probabilistic and artificial intelligence models (Pedersen, 2010).

Analytical models are usually defined with two independent probabilities of causation and geometrical probabilities. Causation probability estimation is based on statistical data analysis with regard to maritime traffic and accidents of a specific waterway. It could take an advantage to indicate a regional risk of collision and grounding (Kaneko, 2002). However, this type of risk analysis approach can only reflect historical condition as it is based on historical data. Even if the method allows to estimate collision frequency in case of changes in traffic volume (Suyi Li et al., 2012), statistical analysis method cannot be utilised for a real-time, dynamic risk analysis and determining causes of emerged risk and it is not advantageous for navigators in terms of decision support purposes (Rowe, 1994).

Geometrical probability estimation basically depends on geometric parameters such as; width of the seaway, size of the vessels, traffic volume, vessels' speed vector (vectorial expression of speed over ground and course over ground), distance and bearing of the targets and other factors. Geometric probability estimation is mostly utilised for capacity estimation studies. They are also the most prominent approach in the literature including ship domain which is commonly employed in the literature for navigational risk determination studies. Besides there are different ship domain definition and perception, it is defined as an area around the ship, where navigators want to keep clear of other ships and objects (Goodwin, 1975). Pietrzykowski (2008) specifies ship domain as an effective sea area around ships that navigators keep to be clear of other targets (Pietrzykowski, 2008). Coldwell (1983) describes as an effective area around the ship which navigators actually keeps free dependent on Target Ships (TS) (Coldwell, 1983). Alternatively, Zhu et al. (2001) depicted ship domain as an intended and desirable area to be kept around the vessel (Zhu et al., 2001). In the light of the above mentioned and all other ship domain explanations can be classified as desirable and efficient ship domain. The domain approach has been adopted for path planning, collision avoidance, collision risk assessment for close encounter situations with the number of diverse shapes, such as polygonal, rectangular, elliptical or circular (Szlapczynski, 2006; R. Szlapczynski & J. Szlapczynska, 2017; Wang, 2010; Zhou & Zheng). However, there is no commonly-held shape of ship domain and empirical study to investigate the best configuration (Rafal Szlapczynski & Joanna Szlapczynska, 2017b). Moreover, it is still not revealed how ship domain is utilized for path planning and risk determination of multi-ship involving situations in real geographical constraints (Y. Wang, 2012). Ship domain is not a sufficient approach to give a decision and early warning support for TSs and constraints out of the domain border. Combination of both causation and geometrical probabilities for risk estimation has some negative aspects, such as assumptions, omissions, and in some cases, overestimation. Pros and cons of the methodology is investigated in literature review section in detail.

Probabilistic models can be assessed as complementary approach to analytical models and their weak aspects (Mazaheri et al., 2014). They analyse collision and grounding accidents from a holistic perspective by using Bayesian Network (BN) or Fault Tree Analysis (FTA) (Mazaheri et al., 2014). Defining the contributor factors of the accident as a degree of belief and participation in the calculations in this way allows Bayesian Belief Network (BBN) method to offer a more realistic solution than the FTA. BBN approach is also considered more suitable for a realistic collision and ground risk analysis by scholars because of the fact that the events must be statistically dependent on the FTA and based on the binary system (Kristiansen, 2010).

In recent years, artificial neural network and fuzzy reasoning methods have been used in order to determine the risk of collision and grounding in line with the developments in artificial intelligence technology. In the literature, fuzzy neural network is also used for the determination of ship domain and its dimensions (Pietrzykowski, 2008). With the determination of the shape and size of the domain based on the fuzzy logic membership functions is an approach decomposed from desired and effective domains.

Although studies will be examined according to the method classification mentioned above, it should be noted that these methods and approaches can be combined and utilised. In other words, these methods are not completely independent approaches.

1.2 Objective and Scope

With the developing technology, electronic navigation technology has become widespread in the sea transportation where approximately 90% of the product transportation is realized in the world (UNCTAD, 2017). In this context, the Electronic Chart and Information System (ECDIS), the Voyage Data Recorder (VDR) and the Automatic Identification System (AIS) are used actively which are mandatory for commercial vessels. Nowadays, data generated by ship electronic navigational devices is used to establish real-time navigational safety for the purpose of preventing grounding and ship-ship collision accidents.

It is obvious that many navigational data obtained from electronic navigational devices and stored in VDR can be utilised more advantageously for safety of navigation rather than utilising them for only basic anti-collision and anti-grounding purposes. Many navigational time dependent data that will be named as dynamic data and some static data that are not time dependent and correspond unchanging data such as ship length, breadth, ship type etc. are continuously stored by the VDR. Whereas, many authorities and scholars define VDR as black-box device which can be used for accident investigation and analysis (IMO, 1997; KONG et al., 2004; Morsi et al., 2010; Piccinelli & Gubian, 2013). Purpose of the thesis is not to apply the real time calculating dynamic navigational risks, that corresponds a real-time computation depending on dynamic data, in the simulator or laboratory environment as in the literature. The objective of the thesis is to create an algorithm that can evaluate the produced navigational data with an appropriate academic method which is convenient to run on board real ship in terms of data communication and provide decision support to watch officers by indicating real time collision and grounding risks.

In the literature, while the ships were evaluated as a single point, the ship figure, which was formed depending on the width and length of the ships, was included in the navigational risk calculation. Most of the previous studies produce only the frequency calculation of the navigational risk, in this study, the combination of frequency and consequence is also addressed. Moreover, lack of any technical training would cause navigational risks ultimately, thus in the lights of the outputs, factors that lead to risk can be assessed and utilised for determining subsequent training needs.

In addition, by means of the navigational risk outputs, personnel evaluation, which is still depending on subjective evaluation of ships' masters, can be carried out objectively in terms of performing the safe navigation. Within this context, the thesis is anticipated to reach some solid targets summarised as follows;

i) Real time dynamic navigational risk assessment tool,

ii) Computations based on multi-point ships' form,

iii) Convenience to run on board real ship,

iv) Utilizable to identify navigational training needs,

v) Utilizable for performing an objective officers' evaluation process.

1.3 Thesis Organization

In Chapter 2, all studies on navigational risk analysis in the literature are discussed in detail. Besides, studies on static navigational risk, collision avoidance, abnormal navigation detection, sinking risk after a collision, collision near misses are discussed in detail in terms of their advantages, solutions they proposed, factors included in the calculations. In addition, developments starting from the emergence of the ship domain concept to date are explained. The different types of proposed ship domains, their calculation methods and the utilised methodology in the calculation of navigational risk are also analyzed in detail. The model proposed in the thesis was compared with all studies in the literature in terms of method, applicability, technical relevance and factors included in the calculations.

In Chapter 3, the methods of obtaining the data required for performing the risk analysis of the algorithm consisting of 4 main modules are explained. In order to perform real-time navigational risk analysis integrated with the ship navigation equipment, the modules where the necessary AIS and electronic chart data are obtained, and the calculations to which the obtained information is subjected, and the steps of creating the user interface by visualizing all final outputs are explained. The process of creating the infrastructure in accordance with The National Marine Electronics Association (NMEA) 0183 standard, which is the data exchange protocol, is also described in detail.

In chapter 4, a comprehensive explanation of the methodology utilised in the thesis is introduced. The concept of fuzzy logic and fuzzy inference method used in the thesis are explained. Fuzzy sets and membership function, fuzzy operators, composition of fuzzy sets, fuzzification process, rule base, inference mechanism and defuzzification stage are explained in detail.

In chapter 5, the application of the fuzzy inference method to the calculation of the collision and grounding risks is explained. Starting from the determining the risk factors stage, expert elicitation, determination of fuzzy sets, rule structures and performing the inference mechanism are described as with application. There exists also a case study in which the developed algorithm is applied for a ship navigating in Istanbul Strait.

Finally, in Chapter 6, the advantages, innovations and applicability of the study, which proposed real-time collision and grounding risk analysis algorithm on board, is discussed. In addition, issues, approaches and methods that can be addressed in future studies are discussed in order to transform probable weaknesses of the algorithm into opportunities.

2. LITERATURE REVIEW

It is an indisputable fact that the safety of navigation is the most essential issue for maritime transportation. With increasing seaborne transportation volume, the marine traffic is getting denser day by day. Increasing marine traffic density brings about marine casualties, which usually ends up with fatalities, injuries, ship loss, cargo damage or loss and pollution events (Arslan & Turan, 2009; Kum et al., 2006). Most frequent marine accidents can be listed as collision, contact and grounding (EMSA, 2019). Accordingly, ship grounding accidents is at the third rank by frequency after collision and contact accidents. Moreover, collision is the most frequently encountering accident at local seaways which has intense marine traffic such as İstanbul Strait, Singapore Strait and Gulf of Finland (Akten, 2004; Klanac et al., 2010; Kujala et al., 2009; Weng et al., 2012).

Many scholars tried to establish models for estimation accidental risk to ensure safety of navigation. There also exist some valuable review studies in the literature which deals with collision and grounding risk calculation models in detail (Goerlandt & Montewka, 2015; S. Li et al., 2012; Mazaheri et al., 2013; Ozturk & Cicek, 2019; Pedersen, 2010; Rafal Szlapczynski & Joanna Szlapczynska, 2017b). In this section of the thesis, significant models will be investigated in terms of their methodologies, factors included to the models, their solutions and applicability to collision or grounding risk. In addition, a critical view is taken in terms of their methodology, applicability, levels of realism and technical relevance.

2.1 Analytical Models

2.1.1 Macduff's model (1974)

Macduff suggested the real grounding risk (P_{RG}) as the product of geometrical probability (P_G) and causation probability (P_{CG}) (Macduff, 1974). By utilising Buffon's Needle Problem, he formulated the geometrical probability for navigating vessels through a channel.

$$P_{RG} = P_G \; x \; P_{CG} \tag{2.1}$$

$$P_G = \frac{4T}{\pi C} \tag{2.2}$$

where T is ship's track length which is function of the size and speed of the ship. C is channel breadth.

Macduff also suggested the collision risk (P_{Coll}) as the product of geometrical in a word spatial probability (P_A) and causation probability (P_{CC}) of collision. He utilised molecular collision theory for calculating geometrical probability of collision.

$$P_{Coll} = P_A \; x \; P_{CC} \tag{2.3}$$

$$P_A = \frac{XL\sin(\theta / 2)}{925D^2} \tag{2.4}$$

Where X is actual length of path, D is distance between vessels and L is length of ship. Grounding and collision models have some objectionable points as;

i) Buffon's needle problem is a method to determine probability of stranding in one-dimensional (1D) environment. Whereas, a solution for ship grounding problem is need to be considered in terms of not only ships' length but also ships' breadth and draft.

ii) Channel width is considered as not change, which is an inconvenient approach for real conditions.

iii) Speed of main ship stream is assumed V and the speed of ship approaching the stream is also assumed V which is an inconvenient approach for real conditions.

iv) Grounding formula can be overestimated especially in case of small degree of θ (S. Li et al., 2012).

v) Causation probabilities (P_{CG}, P_{CC}) models based on statistical analysis of the traffic data and accidents. Macduff's model cannot be utilised to depict a real time navigational risk (Hwang et al., 2016).

2.1.2 Fuji's models (1971, 1974)

Similar to Macduff's model Fuji et al. (1974; 1971) mentioned causation probability (P_C) and an expected number of grounding accidents (N_G) which is a function of traffic density (ρ), width of the shoal (D) and ship's speed (V).

$$N_G = P_C D \rho V \tag{2.5}$$

Fuji proposed a collision model to estimate evasive actions by considering number of passing ships through a specific area;

$$\int_{entrance}^{exit} (\rho D_e V_{rel} / V) dx \tag{2.6}$$

where ρ is ships' density, D_e is evasion diameter V_{rel} is relative speed and V is passing ships' speed. The model can be inadequate in some points listed below;

vi) Similar to Macduff's Model, Fuji's model is based on statistical data and some assumptions (S. Li et al., 2012). Especially, assuming the distribution of traffic density as linear for all time is not acceptable.

vii) The model is influenced by ship particulars, which is the only dynamic elements. Rest of the elements, location-related, are not dynamically changed (Mazaheri et al., 2014).

viii) Ships' drafts, depth and length of channel are not considered in the model.

ix) Fuji's model also overestimates the geometrical probability as it provides a 9.5-16.3 times of the ship's length for evasive manoeuvre, whereas minimum distance between the ships could be three times of ship's length in the reality.

2.1.3 Curtis' model (1986)

In the presence of restricted visibility with geometric probability estimation approach, Minimum Safe Overtaking Distance (MSOD) was proposed considering that an overtaken vessel suddenly makes a turn through a right angle of overtaking vessel (Curtis, 1986). In other words, it is the reaction time dependent minimum parallel distance that the overtaking vessel can make evasive manoeuvre to avoid a collision with overtaken vessel. Figure 2.1 shows MSOD and the situation expressed above.

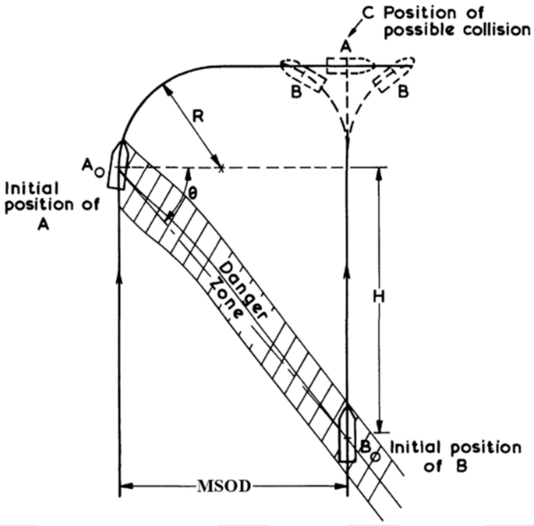

Figure 2.1 : MSOD during overtaking (Curtis, 1986).

Speed, rudder angle and evasive manoeuvre reaction time influence the MSOD. The model has many assumptions and omits that make it unrealistic.

2.1.4 Hara's model (1995)

A qualitative risk evaluation model was suggested by Hara and Nakamura (Hara & Nakamura, 1995). Subjective Judgement value (SJ-value) was determined as an index of subjective collision risk. SJ value was calculated based on simulator experiments. Index of mariners' collision risk feelings, SJ-value is introduced below:

$$SJ_i = a_i\beta + b_i D_r + c_i V_n + d_i \tag{2.7}$$

where SJ_i is subjective judgement value, β is non-dimensional rate of chance on relative bearing, D is relative distance between ships, D_r is non-dimensional relative distance ($D_r = D / L$), V_n is non-dimensional approaching speed ($V_n = V_r / V$), V is speed of OS, V_r is relative speed and a_i, b_i, c_i, d_i are coefficient of each parameter. i is defined as the four encounter situations (1 for head on, 2 for proceeding same way, 3 for crossing from starboard side and 4 for crossing from port side).

2.1.5 Pedersen's model (1995)

Pedersen (1995), in the calculation of geometric probability and then Simonsen (1997) presented important studies. Similar to former, Pedersen suggested the grounding risk as a combination of causation probability (P_C) and expected number of groundings or collisions (F). Causation probability was determined by using FTA. They categorized grounding scenarios into 4 groups. The first two of this groups are given below. The latter two are not investigated as they are out of the scope of thesis and relevant to accidents during the evasive manoeuvre category and named others than formers category.

i) While a ship is enroute, accidents originated from human error or unexpected errors.

ii) When ship is fail to change her course.

Figure 2.2 shows Pedersen's grounding and collision categories.

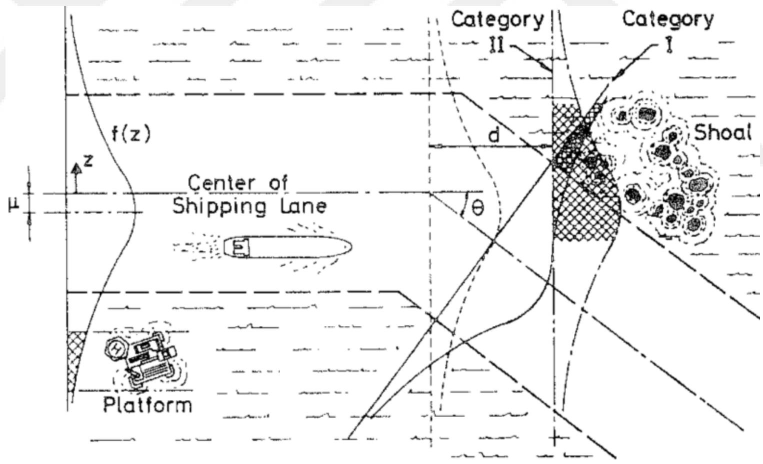

Figure 2.2 : Pedersen's grounding categories (Pedersen, 1995).

For Category 1, Pedersen's expected number of grounding or collision is;

$$F_{Cat1} = \sum_{Ship\,class\,i=1}^{n\,class} P_{ci} Q_i \int_L f_i B_i ds \tag{2.8}$$

For Category 1, Simonsen's expected number of grounding or collision is;

$$F_{Cat1} = \sum_{Ship\,class,i}^{n\,class} P_{ci} Q_i \int_{Z_{min}}^{Z_{max}} f_i(z) dz \tag{2.9}$$

For Category 2, Pedersen's expected number of grounding or collision is;

$$F_{Cat\,2} = \sum_{Ship\,class\,i=1}^{n\,class} P_{ci} Q_i P_0^{(d-a_i)/a_i} \int_L f_i B_i ds \tag{2.10}$$

For Category 2, Simonsen's expected number of grounding or collision is;

$$F_{Cat1} = \sum_{Ship\,class,i}^{n\,class} P_{ci} Q_i e^{-d/a_i} \int_{Z_{\min}}^{Z_{\max}} f_i(z) dz \tag{2.11}$$

where i is number of ship class depending on deadweight or length and type of ship. P_{ci} is causation probability which is a failure rate while avoiding target originated from human error and technical failure. Pedersen defined the causation probability by Fault Tree Analysis (FTA). Q_i annual ship movement number of vessel class i. L is width of the investigated area. f_i is ship track distribution. B_i is collision indicating factor. P_0 is probability of violating ship's position check. d is distance between a target and bend in the route. a_i interval of two successive position check.

Pedersen's model is one of the most frequently employed geometrical model in the literature (Eide et al., 2007; Fowler & Sørgård, 2000; Friis-Hansen & Simonsen, 2002; Hansen et al., 2013; Hansen & Pedersen, 1997; Karlsson et al., 1998; Kristiansen, 2013; Otto et al., 2002).

2.1.6 Kaneko's model (2002)

Kaneko (2002) suggested a geometrical probability model of collision based on two specific scenarios. One is based on random sailing direction within a circular shaped area. Other is based on fixed sailing direction within a rectangular area. When distance between the ships is smaller than r, it is dangerous encountering situation. Within time T, number of encountered ships for the scenario of random sailing direction (λ_{c1}) is:

$$\lambda_{c1} = \frac{4\rho VrT}{\pi}(1+\alpha)E\left(\frac{2\sqrt{\alpha}}{1+\alpha}\right) \tag{2.11}$$

where ρ is ships' average number within the area, V_0 is Own Ship's (OS) speed, V is speed of TSs and $\alpha = V_0 / V$ and;

$$E\left(\frac{2\sqrt{V_0 V}}{V+V_0}\right)=\sqrt{1-\frac{4V_0 V}{V+V_0}\sin^2\theta d\theta} \quad (2.12)$$

where θ is angle between OS's and TSs' directions.

Within time T, number of encountered ships for the scenario of fixed sailing direction is:

$$\lambda_{c2}=\rho V 2rT\sqrt{1+\alpha^2+2\alpha\cos\theta} \quad (2.13)$$

According to results, random sailing direction is observed 10% more dangerous than fixed sailing direction scenario. Kaneko's model is considered more convenient for open sea areas as it needs a uniformed traffic density (S. Li et al., 2012).

2.1.7 COWI models (2008)

COWI model (2008) is another version of Pedersen's model, where Course Over Ground (COG) distribution is used instead of track distribution. Additionally, COWI suggested probability of grounding (P_G) as;

$$P_G=F(\alpha_1)-F(\alpha_2) \quad (2.14)$$

Where F is Gaussian distribution COG of vessels in the vicinity of shallowness. α_1 and α_2 are upper and lower angles of shallowness from the ship, shown in Figure 2.3.

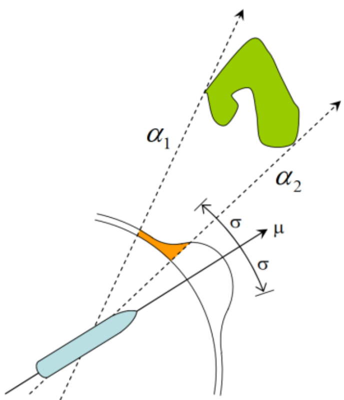

Figure 2.3 : Upper and lower angles of shallowness (COWI, 2008).

COWI also proposed a model to calculate frequency of collision. For parallel waterways (overtaking or head on situations) collision frequency (P_X) is given below:

$$P_X = P_T \, x \, P_G \, x \, P_C \, x \, k_{RR} \quad (2.15)$$

where P_T is frequency of meetings on same route segment, P_G is geometrical probability same in Pedersen's model, P_C is causation probability and k_{RR} is risk reduction factor. In summary, collision frequency is influenced by traffic density of both directions, ships' speed and width, length of route segment, cross track distance from route segment, causation probability and risk reduction factor.

COWI model is employed by other scholars and developed by employing ships' manoeuvrability including draft and turning circle of ships (Montewka et al., 2011).

2.1.8 Montewka's model (2010)

Montewka et al. (2012; 2010) proposed geometrical probability estimation based a Minimum Distance to Collision (MDTC) phenomenon which was defined as the minimum distance between vessels on collision courses at which last effective evasive manoeuvre can be done. Figure 2.4 shows relations between MDTC, collision and safe passing.

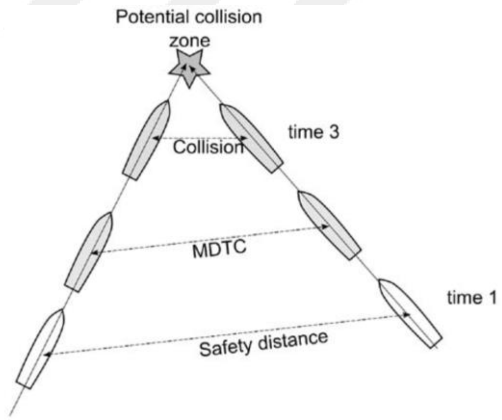

Figure 2.4 : MDTC and its relations (Montewka et al., 2010).

Distance less than MDTC means the collision is unavoidable. Manoeuvrability of ships, angle of intersection and relative bearing of vessels influence the MDTC which is calculated by using molecular collision model (Endoh, 1982). MDTC has different size depending on the different encountering situations (head-on, overtaking and crossing). Unlike Macduff's work, the ship's manoeuvrability was also included in the calculations to create a disc-shaped space around the ship (Macduff, 1974). The quasi-linear modular hydrodynamic model was used to calculate the average manoeuvrings characteristics for the four ship types commonly found in the Gulf of Finland (Montewka et al., 2010).

2.1.9 Zhang's model (2012)

Zhang et al. (2012) suggested a subjective judgement based anti-collision model. Prior the anti-collision algorithm a Restricted Area (RA) was created to identify risky situations. The RA, in which collision is inevitable if another ship invades it, is different from ship domain and quite smaller than the domain. Size of RA was determined as a result of the survey conducted with Nantong pilots. Accordingly, ellipse shaped RA has length of 2L on ahead, width of 2B on both sides and length of 1L on stern, where L is length of the addressed ship. Figure 2.5 shows generated RA with its dimensions. Mathematical expression of RA is given below:

$$\frac{x^2}{(2B)^2} + \frac{y^2}{([1+\mathrm{sgn}(y)]L + [1-\mathrm{sgn}(y)]L/2)^2} \leq 1 \tag{2.17}$$

Where x *and* y are the starboard and heading axis respectively and $\mathrm{sgn}(y) = \{\ 1,\ y \geq 0\ \ and\ \ -1,\ y < 0$.

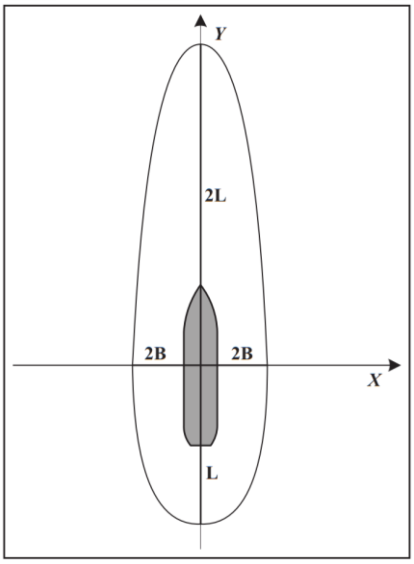

Figure 2.5 : Restricted area with dimensions (Zhang et al., 2012).

In summary, length of ships and intersection angle of headings are the factors affecting the avoidance algorithm in the model.

2.1.10 Oh's model (2015)

In South Korea, a model based on geometrical probability estimation was proposed to determine regional near miss ratios for the Wando region (Oh et al., 2015). AIS and radar data of ships in vicinity was obtained for 72 hours. A barrier limit, based on Closest Point of Approach (CPA) and Time to Closest Point of Approach (TCPA) was determined inspired by the Frandsen's bumper area study (Frandsen et al., 1991). Accordingly, they fixed CPA to 0.3 nautical mile (nm) and TCPA to 5 minutes (min). Thus, number and then rate of near misses by categorizing into different encounter situations were determined. The positions of emerged near misses are also shown on the chart by using MATLAB software. The model would be helpful in pointing out the regions that should be especially focused on Vessel Traffic Service (VTS) in the area. However, the model needs to be developed in some respects. Instead of merely CPA and TCPA-oriented model, more factors should be taken into account. In addition, similar CPA and TCPA values in all regions will not be safe and efficient, they need to be evaluated and revised depending on the region.

2.1.11 Zhang's model (2015)

Zhang et al. (2015) proposed an expert judgement based model for detecting possible near misses of ship collision. An indicator, Vessel Conflict Ranking Operator (VCRO) was developed, which enables to estimate the severity of pairwise ship encounters. Distance of encountered ship, relative speed and variance of ships' heading were considered as the VCRO influencing factors.

2.1.12 Hwang model (2016)

In this model, a spatial collision risk analysing approach is suggested (Hwang et al., 2016). Regional risk points were identified by determining Safety Index (SI) for Osaka Bay, where the whole area is divided into 32X32 sections. Weights of predefined factors are computed by 1-9 scaled questionnaire. Quantification of the factors' weight (I_{ij}) is given below:

$$I_{ij} = \sum_{1}^{N} R_{ij} x \frac{1}{N} \tag{2.16}$$

where R_{ij} is answer degree for j th Element of i th item, N is number of correspondents, i is item number of questionnaire and j is element number of each item.

SI was computed as following:

$$SI = \sum_{1}^{n} \sum_{1}^{i} I_{ij} \tag{2.17}$$

where n is number of vessels in each section.

Type and length of ship, relative speed, distance, encounter situations, time of day, day of week are the factors influencing Safety Index. There exists no relation between the factors and each one considered independent. Whereas, most of the factors may affect each other like relation between distance and relative speed for diverse encounter situation. Moreover, probable local constraints and shallowness influence the distance of ships and spatial safety index for each section need to be considered.

2.1.13 Altan’s model (2018)

Altan and Otay (2018) conducted a molecular collision theory based collision probability estimation approach for İstanbul Strait. Geometrical probability estimation was performed based on one-year AIS data of İstanbul Strait. They preferred to use encounter term instead of calculated collision probability based on molecular collision theory. They divided the Istanbul Strait into 13 regions where North and South bound vessels were mostly en-route and then these regions were divided into a total 484 cells to analyse. Speed Over Ground (SOG), COG, ships’ positions, Length Over All (LOA) and breadth were included to calculations.

2.2 Probabilistic Models

2.2.1 Amrozowicz’ model (1996)

Amrozowicz (1996) proposed a FTA structure for risk analysis of tanker grounding accident. There were two exclusive intermediate event under the top event as; powered grounding and drift grounding where the basic events were determined by expert judgement and using historical data. FTA approach, which was later rendered dynamic by Şenol and Şahin (2016), consisted entirely of static inputs in 2.2.1 Amrozowicz' model.

2.2.2 Ramboll model (2006)

Ramboll (2006) produced a model by converting FTA of Pedersen's model into BBN. Ramboll has included only the visibility factor as new to the causation probability calculation. In the model, geometrical probability calculation was integrated to nodes of the network. After the calculation of the causation probability nodes is completed, the consequence part, which includes cargo and oil spill or human causalities, is integrated into the model.

2.2.3 Uluscu's model (2009)

Uluscu et al. (2009) proposed a spatial risk analysis approach for Istanbul Strait by utilising paired-comparison approach based on probabilistic arguments that was summarised as accidents, their consequences, situations, historical data and expert opinions. Two-tier calculation was performed for consequence determination. In the first stage, collision, grounding, ramming and fire/explosion accidents were discussed, where in the second stage, the subsequent probable accidents were discussed. The consequence tier was categorised as damage of properties, human causality, environmental damage and impediment on traffic. In the study, Istanbul Strait was divided into 21 slices and in addition to expert opinion, AIS data for 2005-2006 were also used. Ships' type, length, age, flag, pilot request and tugboat request were included to vessel attributes and distance between sequential vessels, current, geographical difficulties of related slice and density of local traffic were considered as environmental attributes.

Although it is very comprehensive study in terms of the factors included in the calculations, it may not be sufficient to calculate the dynamic navigation risks. Because regional risk factors are based on historical data and are deprived of real-time traffic information and evaluation of marine environment.

2.2.4 Montewka's model (2014)

Montewka et al. (2014) proposed a BBN based model to compute the risk of sinking for RoPax ships after an open sea collision in the Gulf of Finland. It is one of the few models that includes severity of the accident to the calculations. The model has four main factors; collision factor, capsizing-relevant factor, response to the accident factor and consequences factor. Collision factor is based collision angle and speed which cause a rupture on the inner hull of struck RoPax vessel. To this end, they calculated the collision rate for the RoPax vessels according to AIS data. Ships' types, ships' sizes, collision angles, collision speed and the time of day of a probable collision were accounted factors in the model.

2.2.5 Senol's model (2016)

Senol and Sahin (2016) proposed a novel approach to calculate both risks of collision and grounding based on Real-Time Continuous Fuzzy Fault Tree Analysis (RC-FFTA). Contrary to generic Fault Tree Analysis (FTA), which is a risk assessment tool for the fields of risk, safety, and reliability, a hybrid model using static and dynamic data are developed for navigational risk calculations. The developed RC-FFTA model is used for a dynamic environment, in which parameters such as speed, distance, meteorological conditions, etc. communicate directly through the algorithm. In other words, it proposes a RC-FFTA model which handles real-time continuous input data. Since the conventional FFTA methods deal with obtaining the failure possibilities of Basic Events (BEs), the proposed model suggests obtaining the failure possibilities of BEs when combined with their impacts on the Top Event (TE). In this model, fault trees of collision and grounding are studied separately where there are three types of BEs as sensor BE, manual BE and the conventional BEs. Sensor BE corresponds dynamic time dependent data such as speed and COG where manual BE corresponds operator dependent data such as meteorological information and conventional BE stands for BE computed by statistical data or fuzzy approach. Dynamically non-changing values of conventional BEs are computed by using the fuzzy approach, sensor and manual BEs for dynamically changing diverse situations are calculated by predefined the fuzzy scales. They generated two separate fault trees for collision and grounding risks. The purpose of the study is to provide a real-time continuous fuzzy fault tree analysis model for dynamic environment to prevent undesired events in the complex, vague, complicated, and uncertain systems. On the one side of the fault tree, there are BEs obtained by statistical data or by fuzzy based expert elicitation method, while there are dynamic BEs calculated by ship dynamics on the other side. Proposed model analyses risks collision and grounding depends on multi-parameters, such as cross track error, closeness to shallowness, CPA, Bridge Navigational Watch Alarm

System (BNWAS) resetting period, and the rate of plotted vessels where they suggest a decision support system for maritime industry to provide safety of life, property, and less pollutions in the marine ecology.

In the model, there are fuzzy scales created by field expert consultation for each dynamic BE. In the light of the information obtained, the BEs are compared with the Fuzzy scales and the corresponding value is input dynamically to the fault tree. Modelled factors influencing the grounding and collision accidents are listed below:

i) Closeness to shallowness: It was expressed as a temporal expression of distance. In other words, it is calculated as a division of the closest distance to unsafe waters to the speed of the vessel.

ii) Resetting period of Bridge Navigational Watch Alarm System (BNWAS): BNWAS detects the activities of the officers of the watch and determines the lack of operators that may cause an accident. The system senses the situational awareness of officers of watch and warns the master of the ship or others if needed. The system counts down from 12 min. If there exists no situational awareness, it firstly warn with a visual indication, and then, alerts audibly. Countdown is always reset if and only there is a motion at the location of a proper look-out, via the equipment used in this location. BNWAS resetting frequency means how frequent the watch officer checks the navigational status. In the model, after expert consultations, the risks of collision and grounding are computed by considering the reset frequencies of BNWAS within 12 min and the resetting seconds of audible alerts after visual indication and 12th minute It was modelled as a dynamic factor in the literature as never before.

iii) Deviation from intended course: Assuming that the navigator had planned a safest route and thus the amount of deviation from this route was included as a dynamic factor in the model.

iv) Closest point of approach (CPA): As in many models, it is one of the most important factors in the calculation of collision risk. In this model, it is included in the calculations as a dynamic factor of collision risk.

v) Rate of plotted vessels: rate of plotted vessels in the vicinity of 10 nm. distance with the maximum CPA value of 2 nm.

vi) Meteorological conditions: In the model, it is also modelled fuzzy scale based dynamic factor referring to Beaufort Scale.

2.3 Artificial Intelligence Models

2.3.1 Kijima's model (2001)

Kijima and Furukawa (2001) proposed a study on collision avoidance system by using fuzzy reasoning (inference) approach. In order to design an autonomous system, it is essential that the system is able to perceive the risk of collision. For this purpose, the risks of collision (C_R) were calculated firstly. Non-dimensional form of CPA using ship's length (L), (CPA/L), and TCPA were employed as it was previously used in the literature (Tanaka, 1994). They used three linguistic variables (zero neighbourhood (ZO), Positive small (PS), Positive big (PB)) for CPA/L and four linguistic variables (negative (N), zero neighbourhood (ZO), Positive small (PS), Positive big (PB)) for TCPA. According to the output, defuzzified value of the reasoning system, they identified three rules for avoidance actions. Then fuzzy reasoning based avoidance calculations were carried out which are out of thesis' scope.

2.3.2 Liu's model (2005)

Liu and Shi (2005) proposed a collision avoidance model based on fuzzy neural inference network (Liu & Shi, 2005). There are three subnets for classifying encounter situation and collision avoidance actions, membership calculation of the speed ratio and magnitude of evasive action and reaction time. First two subnets' weights were obtained by self-learning method employing 24 scenarios. The weight of the latter was obtained from their experiences. First two steps of the calculation are the stages of collision risk detection. Last subnet of the model works output values of the formers. Speed of ships, range, CPA, water area (limit waters, coastal and open sea) and time of day (night and day) factors were utilised in the phase of collision risk determination.

Such methods often give more realistic results than a complex and assumption-based analysis. But the most important consideration is to select the correct scenario and sample data for training of networks. The model can be extended by considering some additional input factors such as; type and size of ships, manoeuvrability of the ships, visibility and etc.

2.3.3 Kao's model (2007)

A vessel collision early warning model was proposed as a decision-support system for VTS operators (Kao et al., 2007). C++ and AVENUE languages were utilised for integrating AIS data to Marine Geographic Information System (MGIS) and running the algorithm. They determined size of ship-domain-like circular guard rings for ships by utilising fuzzy reasoning method. There were three inputs (ships' length, speed and sea state) and one output (radius of guard ring) in the reasoning system. After determining the guard ring for the ships in the first phase of the algorithm, they calculated the danger index by using the radical axis method at the intersection of the rings. Figure 2.6 shows intersection of the rings and radical axis.

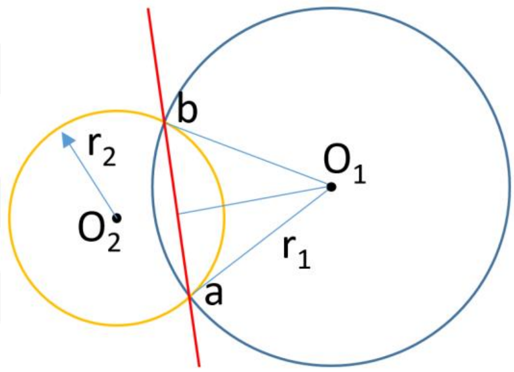

Figure 2.6 : Intersection of the rings and radical axis.

The model is quite fascinating and appropriate for its purpose. Also utilising radical axis method to determine the risk level is very extraordinary and novel solution. However, the inputs influencing radius of the guard rings can be extended to find out a more reliable outcome by considering visibility, ships' type and etc.

2.3.4 Park's model (2012)

Park et al. (2012) proposed a fuzzy reasoning based abnormal navigation detection model for VTS centres. Speed and course change over the last 9 minutes were suggested as an indicator of abnormality. For VTS operators, an algorithm was developed to point out the abnormality of ships, which is dependent to only speed (ΔV) and course ($\Delta\varnothing$) variations. Each input is expressed by five linguistic variables (zero, small, mid, big, very big). Within the fuzzy reasoning process, 25 rules have been prepared and all probable speed and course changes of the vessels are covered. Figure 2.7 summarizes reasoning rules of abnormal navigation. Proposed model can be a systematic approach to establish any abnormal actions at sea. However, there are some technically weak points of the paper listed below rather than the fuzzy reasoning approach:

i) The abnormality indicator should not be influenced by the speed and course variations only. At the same time, grounding and collision situations should also be considered simultaneously.

ii) For the intense waterways, for example Istanbul Strait, many local traffic elements are constantly changing their speed and course within a very short time. VTS operators with the proposed model will be exposed to too many alarms, many of which could be unnecessary.

iii) Reasoning rules will cause overestimation on abnormality. For example, *"if course variation is Zero and speed alteration is Very Big then abnormality is Very Big"* rule expresses a very normal condition of vessel departing from port or anchor which is not an indicator of abnormality.

$\sum \Delta V$ / $\sum \Delta \varnothing$	Zero	Small	Mid	Big	Very Big(VB)
Zero	Zero	Small	Mid	Big	VB
Small	Small	Mid	Big	VB	VB
Mid	Mid	Big	VB	VB	VB
Big	Big	VB	VB	VB	VB
Very Big(VB)	VB	VB	VB	VB	VB

Figure 2.7 : Reasoning rules of abnormal navigation (Park et al., 2012).

2.3.5 Bukhari's model (2013)

Bukhari et al. (2013) proposed a fuzzy reasoning based vessel collision risk assessment system for VTS centres. CPA, TCPA and Variance of Compass Degree (VCD) were considered as inputs of reasoning system. Relevant data were obtained a simple radar from VTS centre. VCD was used as the relative expression on variance of the angle between ships because the ship information was taken from the radar at the VTS centre. They carried out to test and validate their model in the simulator environment. Though, the model has similarities with the Kijima's Model (2001), the algorithm is well organized because it simultaneously calculates speed vector, relative bearings and of course CPA, TCPA and VCD of all ships in vicinity.

2.3.6 Li's model (2013)

Li and Pang (2013) proposed a new approach to collision risk determination by employing Dempster–Shafer (D-S) evidence theory which is widely used, flexible and uncomplicated method for dealing with incomplete and uncertain information. The theory enables to verify uncertainties of statistical inference by associating evidences obtained from some sources and access to a belief degree. A radar processing module was also developed as they obtained radar data for their calculations. CPA, TCPA and distance to TS were included into the model where only probability estimation was conducted and results of a probable collision were not considered.

2.3.7 Chen's model (2014)

Chen et al. (2014) proposed a collision risk calculation method by utilising fuzzy reasoning approach. The model was programmed in C# environment. In the proposed model, two-step fuzzy reasoning method was employed. Similar to Kijima's Model (2001), CPA and TCPA parameters are calculated using state information of vessels obtained from radar. Firstly, fuzzy reasoning based calculation of first collision risk (C_1) with the CPA and TCPA inputs was carried out. Secondly, second collision risk (C_2), influenced by CPA, TCPA, distance between the ships and bearing of encountered ship was calculated. At the second step, fuzzy reasoning calculation was carried out with the inputs of C_1 and C_2 and then, final collision risk was determined.

Fuzzy reasoning approach is quite appropriate for the dynamic calculation of navigational risk, but there exist some negative aspects of the model. Second collision risk and the factors were not mentioned briefly. Although a fuzzy reasoning table was given for C_1, a similar table was not available for C_2. On the other hand, the model can be used for probability estimation purposes as there is no consequential input to consider about a collision risk. They also considered the vessel as a single point which may lead to unrealistic estimations as a vessel has specific length and width.

2.3.8 Simsir's Model (2014)

Simsir et al. (2014) proposed an artificial neural network (ANN) based decision support system for collision avoidance. The model was designed and employed for İstanbul Strait. The philosophy of the model is to estimate the positions of the ships three minutes after by considering initial position and COG vectors. After estimation stage, it was aimed to warn the officers and VTS operators, if the ships are in danger of collision. Although ANN method was employed which enables to obtain realistic results, the model is incomplete and inaccurate in terms of technical aspects:

i) Location estimation for next three minutes by using the initial position information and COG vector will not be appropriate for waterways such as İstanbul Strait, which is the scope of the study. Because in such waterways requiring many sharp turns, the position after three minutes may not be accurately estimated by only with mentioned inputs.

ii) The model mentioned the use of the Levenberg-marquardt learning algorithm, but the inputs are not clearly specified. (Dias et al., 2006; Fachinotti et al., 2011; Marquardt, 1963).

iii) It will be better to revise the model to detect not only collision situation but also close quarter situations and warn relevant parties.

2.3.9 Goerlandt's model (2015)

Goerlandt et al. (2015) proposed a ship collision alert system by utilising Sugeno Type fuzzy reasoning approach for open seas. The model uses the most factors influencing collision risk among the fuzzy reasoning based models in the literature. CPA, TCPA, bearing, Bow Cross Range (BCR) and Bow Cross Time (BCT) of TS, visibility, time of day and wave condition factors were included to the system. Unlike the formers, Sugeno type fuzzy reasoning method was also used. For that respect, weight of each factor was determined by analytical hierarchy process (AHP) which is an expert elicitation method. In addition, different reasoning rules were formed for different encounter situations. Goerlandt' Model shows state-of-the-art in dynamic collision risk calculation by using fuzzy reasoning approach.

2.3.10 Pratiwi's model (2017)

Similar to the Chen's Model (2014), fuzzy reasoning method was employed to determine risk level of collision in Madura Strait (Pratiwi et al., 2017). CPA and TCPA was taken into consideration for calculations. Relevant data were obtained from AIS device. Seven real data based case studies were conducted in the paper. Even though, as before, this method is supported by the fuzzy logic method that could be one of the most prominent approach which can reflect risk perception of humankind, it is conspicuous that the model needs to be developed in some certain aspects:

i) Model needs to be extended by considering some additional inputs such as speed, length and width of ships', bearing of targets etc.

ii) As in the formers, the ship's width and length were neglected and the ship was considered as a single point which is a preposterous omit.

Consequently, titles of the studies other than ship domain models, that will be investigated in the next, their researchers and publishing years will be expressed by letter code as shown in Table 2.1. Table 2.2 provides a summary of the investigated studies in terms of which problem they solved, which methods they utilised, which dynamic factors they involved in the calculation, and their Convenience for Dynamic Real Time Risk Analysis (CRA).

Table 2.1 : Letter codes of investigated models.

Letter Code	Publishing Year	Name of Research	Researcher(s)
M1	1971 – 1974	The analysis of traffic accidents – Some factors affecting the frequency of accidents in marine traffic	Fuji et al.
M2	1974	The probability of vessel collisions	Macduff
M3	1986	A ship collision model for overtaking	Curtis
M4	1995	A comprehensive assessment system for the maritime traffic environment	Hara & Nakamura
M5	1995	Collision and grounding mechanics	Pedersen
M6	1996	The quantitative risk of oil tanker groundings	Amrozowicz
M7	1997	Mechanics of ship grounding	Simonsen
M8	2001	Design of automatic collision avoidance system using fuzzy inference	Kijima & Furukawa
M9	2002	Methods for probabilistic safety assessments of ships	Kaneko
M10	2005	A fuzzy-neural inference network for ship collision avoidance	Liu & Shi
M11	2006	Navigational safety in the sound between Denmark and Sweden	Ramboll
M12	2007	A fuzzy logic method for collision avoidance in vessel traffic service	Kao et al.
M13	2008	Risk analysis for Sea traffic in the area around Bornholm.	COWI
M14	2009	Risk analysis of the vessel traffic in the strait of Istanbul	Uluscu et al.
M15	2010 – 2012	Probability modelling of vessel collisions – Determination of collision criteria and causation factors appropriate to a model for estimating the probability of maritime accidents	Montewka et al. and Montewka et al.
M16	2012	A novel approach for assistance with anti-collision decision making based on the International Regulations for Preventing Collisions at Sea	Zhang et al.
M17	2012	Implementation of an intelligent system for identifying vessels exhibiting abnormal navigation patterns	Park et al.
M18	2013	An intelligent real-time multi-vessel collision risk assessment system from VTS view point based on fuzzy inference system	Bukhari et al.
M19	2014	A framework for risk assessment for maritime transportation systems - A case study for open sea collisions involving RoPax vessels	Montewka et al.
M20	2014	Composition ship collision risk based on fuzzy theory	Chen et al.
M21	2014	Decision support system for collision avoidance of vessels	Simsir et al.
M22	2015	A Study on the risk analysis based on the trajectory of fishing vessels in the VTS area	Oh et al.
M23	2015	A method for detecting possible near miss ship collisions from AIS data	Zhang et al.
M24	2015	A risk-informed ship collision alert system: Framework and application	Goerlandt et al.
M25	2016	A new risk evaluation model for safety management on an entire ship route	Hwang et al.
M26	2016	A novel real-time continuous fuzzy fault tree analysis (RC-FFTA) model for dynamic environment	Senol & Sahin
M27	2015	Fuzzy Inference System for Determining Collision Risk of Ship in Madura Strait Using Automatic Identification System	Pratiwi et al.
M28	2017	Spatial mapping of encounter probability in congested waterways using AIS	Altan & Otay

Table 2.2 : Summary of the models.

Letter Code	Problem	Method	Factors	CRA
M1	Collision and Grounding risk	Analytical	Traffic density, width of the shoal, speed, evasion diameter, relative speed, passing ships' speed.	NO
M2	Collision and Grounding risk	Analytical formulation of molecular collision theory	Traffic density, track length, channel breadth, length of path, distance between vessels, length of ship.	NO
M3	Collision avoidance	Analytic geometry solution	Speed, rudder angle and evasive manoeuvre reaction time	YES
M4	Collision risk	Analytical formulation with subjective judgement value	Relative bearing, relative distance between ships, length of OS, speeds of ships	NO
M5	Collision and Grounding risk	Analytical and probabilistic (FTA)	DWT, length, type of ship, width of area, track distribution, annual ship movement, distance to bend, position fixing interval	NO
M6	Grounding risk	Probabilistic with FTA	NIL	NO
M7	Collision and Grounding risk	Analytical and probabilistic (FTA)	DWT, length, type of ship, width of area, track distribution, annual ship movement, distance to bend, position fixing interval	NO
M8	Collision avoidance	Artificial intelligence with fuzzy inference	CPA, ship's length, TCPA	YES
M9	Collision risk	Analytical formulation with probabilistically obtained consequence	Average ship's number, speeds of ships, angle between OS and TS	NO
M10	Collision avoidance	Artificial intelligence with fuzzy neural inference	Speed of ships, range, CPA, type of waterway and time of day	YES
M11	Collision and Grounding risk	Analytical and probabilistic (BBN)	DWT, length, type of ship, width of area, track distribution, annual ship movement, distance to bend, position fixing interval	NO
M12	Collision risk	Artificial intelligence with fuzzy inference	ships' length, speed and sea state	YES
M13	Collision and Grounding risk	Analytical and probabilistic (FTA)	DWT, length, type of ship, width of area, COG distribution, annual ship movement, distance to bend, position fixing interval	NO
M14	Collision risk	Probabilistic with paired-comparison	Ships' type, length, age, flag, pilot request and tugboat request were included to vessel attributes and distance between sequential vessels, current, geographical difficulties of related slice and density of local traffic	NO
M15	Collision risk	Analytic geometry solution	Manoeuvrability of ships, angle of intersection and relative bearing of vessels	NO
M16	Collision avoidance	Analytical	Length of ships and intersection angle of headings	NO
M17	Abnormal navigation detection	Artificial intelligence with fuzzy inference	speed and course variation of ships	NO
M18	Collision risk	Artificial intelligence with D-S evidence theory	CPA, TCPA and distance to TS	NO
M19	Sinking risk after a collision	Probabilistic with BBN	Ships' types, ships' sizes, collision angles, collision speed and the time of day of a probable collision	NO
M20	Collision risk	Artificial intelligence with fuzzy inference	CPA, TCPA, distance, bearing	YES
M21	Collision risk	Artificial intelligence with neural network	initial position and COG vectors	YES
M22	Collision risk with near miss	Analytical	CPA and TCPA	NO
M23	Collision risk with near miss	Analytical	Distance of encountered ship, relative speed and variance of ships' heading	NO
M24	Collision risk	Artificial intelligence with fuzzy inference	CPA, TCPA, bearing, BCR and BCT of TS, visibility, time of day and wave condition	YES
M25	Collision risk	Analytical formulation with subjective judgement and safety index	Type and length of ship, relative speed, distance, encounter situations, time of day, day of week	NO
M26	Collision and Grounding risk	Probabilistic with fuzzy FTA	Closeness to shallowness, ii) Resetting period of BNWAS, Deviation from intended course, CPA, rate of plotted vessels, meteorological conditions	YES
M27	Collision risk	Artificial intelligence with fuzzy inference	CPA and TCPA	YES
M28	Collision risk	Analytical formulation of molecular collision theory	SOG, COG, ships' positions, LOA and breadth	NO

2.4 Ship Domain Models

In this section, ship domain studies in the literature were examined collectively and they are classified in terms of ship domain descriptions, the methods for determining the ship domain, the factors involved in the calculation and the purposes of ship domain. There exist valuable studies dealing with analysis of ship domains and literature survey studies which are utilised in this thesis. (Baran et al., 2018; Mazaheri & Ylitalo, 2010; Rafal Szlapczynski & Joanna Szlapczynska, 2017b; Tam et al., 2009; Wang et al., 2009; Y. Wang, 2012).

2.4.1 Descriptions of ship domain

There are different descriptions of ship domain phenomenon in the literature. According to Fuji (1971), it is a domain around the ships where other ships have to avoid to enter. In other words, give way ship is to be clear from stand-on ship. According to Goodwin (1975), it is the distance the navigators want to stay away from other ships. Coldwell (1983), on the other hand, defined it as the distance which the navigators keep clear from other ships. In other words, the navigator tries to keep clear his own domain from any kind of targets. Kijima and Furukawa (2003) defined it as an area around the both OS and TS where none of the domains violated by other ship. It is understood that the ship domain definition is quite different based on which ship should remain safe from which domain. According to aforementioned approaches of the studies, it is possible to make four diverse groups depending on the domain violation principles of the ships (Rafal Szlapczynski & Joanna Szlapczynska, 2017b):

i) Ship domain of OS shall not be violated by any TS (a)

ii) Ship domain of TS shall not be violated by OS (b)

iii) Either OS and TS shall not violate domain of the each other. (c)

iv) Ship domains of the both OS and TS shall not be overlapped. (d)

Figure 2.8 indicates summary of four domain violation groups (a-d).

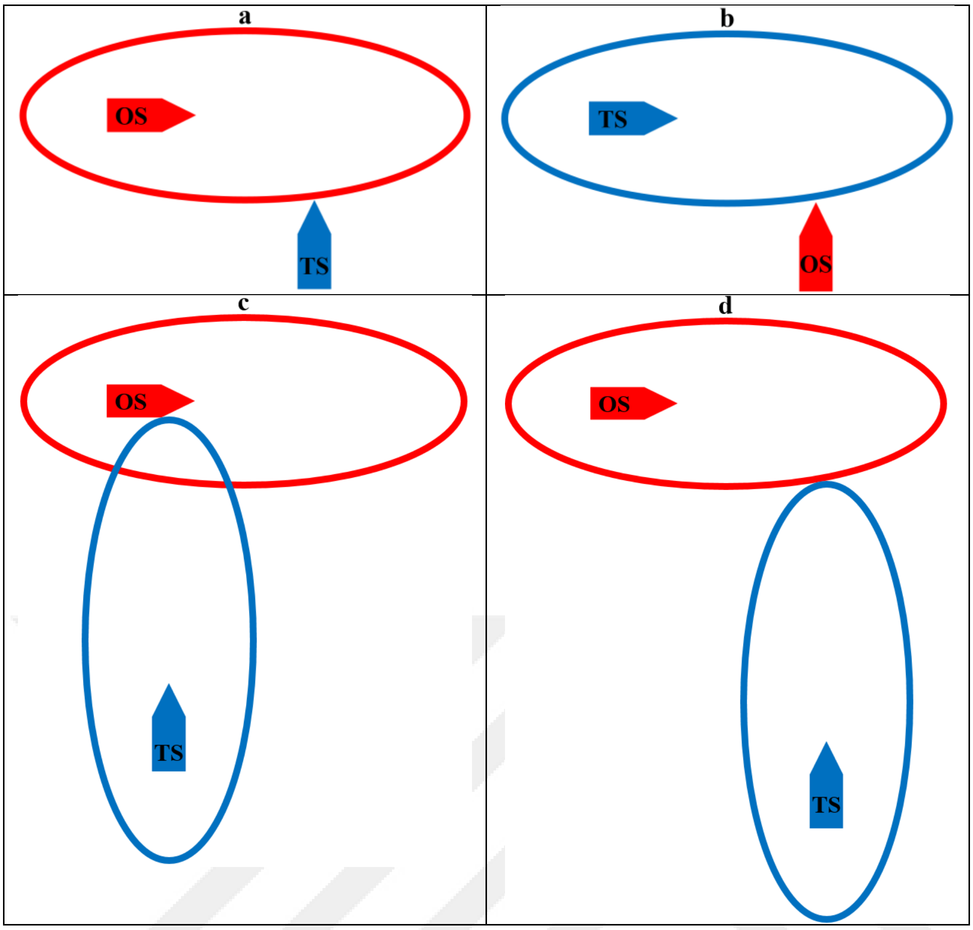

Figure 2.8 : Domain violation groups.

2.4.2 Methods for determining ship domain

There exist considerable amount of methods and approaches used to create domain models. It is commonly possible to classify them as methods based on experimental data, analytical formulation and artificial intelligence.

What is fundamental in experimental data-based methods is to determine the ship domain with a statistical approach by using simulator outputs, radar and lately prevalent AIS data. Within this scope, the domain is created based to the actual navigational conditions and CPA value of the ships by using "local maximum" or a combination of "local maximum" and "minimum" values. In this way, a qualitative analysis of the domain size and shape is determined by using statistical method based on historical data of only traffic density, size, speed and encounter situations factors. It should also be noted that this method will only reveal a domain model which is specific to the analysed sea area. Therefore, it is impossible to employ any obtained size and shape of the domain to another waterway.

Another important point of such approaches is the omission of the marine environment and the factors that may temporarily hinder marine traffic. In addition, the classification of the analysed region in terms of the factors affecting the coastal structure and maritime traffic will be correct and safe solution by determining different domains for each sub-region. For example, the domain study specified for a particular narrow water general does not consider the points where the width of the field changes, and therefore does not provide a suitable domain shape and size for all narrowing and expanding regions.

Scholars lately proposed a quantitative approach, an analytical solution, to complement the weaknesses of experimental data-based models. Thanks to this method, many factors such as speed, length and width of ships, relative bearings, manoeuvrability of ship, geometric dimensions are included in the calculations of domain size and shape determination. The basis of this approach is largely subjectivity and the analytical formulas created may vary depending on the researcher or the consulted experts' opinions. In addition, the factors included in the calculation and the way they are included in mathematical calculations vary depending on the perception of the researcher. While this approach allows more factors to be included in the calculation than the previous one, all possible factors, and in particular the environmental effects and the human factor, cannot be included properly. The analytic method is still the most preferred and studied approach in the literature.

Artificial intelligence methods provide more benefits than the previous two in terms of reflecting the simulator experiments and professional experience of the experts in the calculations. Thanks to this approach, human and environmental factors as well as many other factors are included in the calculations with more reasonable and convenient way to human thinking and perceiving mechanism.

2.4.3 Types of ship domains

Although it is possible to investigate ship domain models under geometrical probability estimation, it has been examined under a separate title because it is a widely used method in the literature and is modelled with different approaches. Ship domain was firstly proposed by Fuji and Tanaka (1971) and defined as an area around the vessels which navigators avoid to enter. They used radar data for determining the boundary of domain as local maximum value of distance distribution curve of surrounding vessels. As shown in Figure 2.9, his domain has an elliptic shape as a proportion of ship length (L). Semi-major axis (r) and semi-minor axis (s) are formulated as follows:

$$r = 7L \mp L$$
$$s = 3L \pm 0.5L \tag{2.18}$$

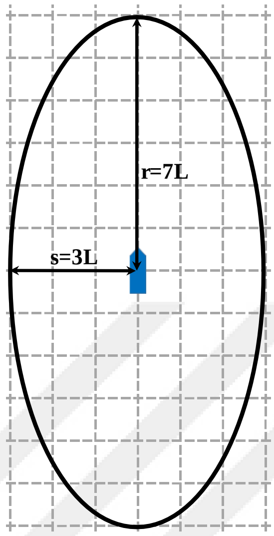

Figure 2.9 : Fuji's ship centred domain.

Fuji's domain was followed by Goodwin's (1975), Davis' (1980) and Coldwell's (1983) domains (Coldwell, 1983; Goodwin, 1975). Goodwin also used radar data and suggested that International Regulations for Preventing Collisions at Sea (COLREG) is affecting navigator's behaviour. She proposed a three sectored domain based on head-on, crossing and overtaking situations. Length between perpendiculars (LBP) and Gross Tonnage (GT) of ship were taken into consideration for determining the boundary distance of the domain which was defined as the area which consists of three circular sectors with 112.5°, 112.5°, and 135° degrees from ship's centre of gravity. She mentioned the local maximum is not sufficient to depict range of domain boundary named as *"domange"*, as there could be data noise and it is proposed to consider a local minimum and a maximum value for ship domain calculation. Figure 2.10 indicates Goodwin's ship domain.

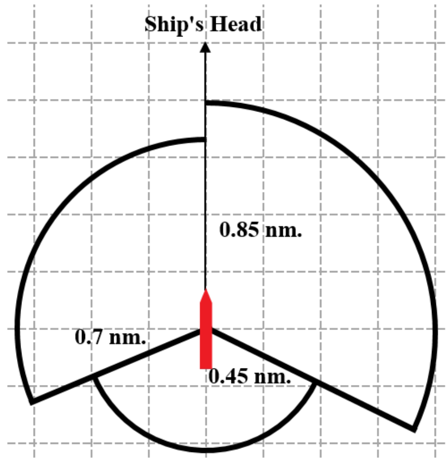

Figure 2.10 : Goodwin's ship domain and its dimensions.

Tak and Spaans (1977) developed a hybrid elliptic ship domain benefitting Fuji's and Goodwin's domain for capacity estimation (Van der Tak & Spaans, 1977). Shape of the domain was inspired by Fuji, while distances of domain boundary and effects of encounter situations on the domain was inspired by Goodwin. They shifted vessel's position from centre to backward and heading was turned to port with an angle based on TS and any other target which creates a certain risk for OS. Vessel's manoeuvrability, navigator's qualifications, psychological factors, reaction time, and the environment factors were considered as influencing factors.

Davis et al. (1980, 1982) proposed a new domain named as *"arena"* which is a mathematically modified simulation version of Goodwin's ship domain (Davis et al., 1980, 1982). Distinct sectors at the angle of sidelights and stern light were rehabilitated and proposed a new area in the form of a circle. Distances from ship of the first off-centred circular domain were determined by simulation results depending on expert judgements. He suggested that earlier domain distances are insufficient to perform an evasive manoeuvre and thus he suggested an area that could be defined as an action domain which gives an idea for evasive manoeuvre time and is more suitable for realistic traffic behaviour (Tam et al., 2009). Radius of the proposed domain was calculated as 2.7 nm. position of the OS was located with 199° clockwise angle and 1.7 nm distance of the centre. Figure 2.11 shows the proposed arena.

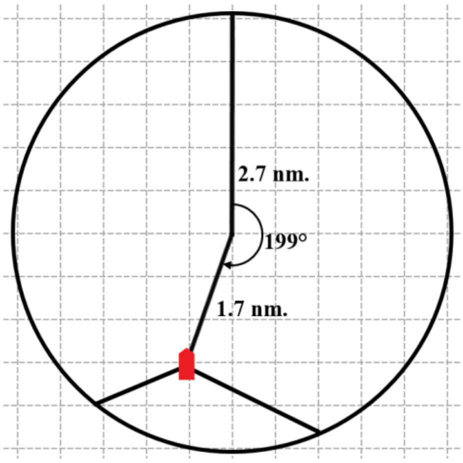

Figure 2.11 : Davis' modified ship domain.

Coldwell (1983) also proposed an elliptic ship domain by considering encounter situations of head-on and overtaking (Coldwell, 1983). He also used radar data for statistical analysis of marine traffic for a specific restricted area. Distance of domain boundary was determined as the distance from the central ship at which the density of surrounding vessels reach local maximum. Coldwell firstly proposed off-centred elliptic domain for head-on encounter in the literature. Semi-major axis (r) and semi-minor axis (s) which are determined as multiplication of ship length (L) are formulated for head-on and overtaking encounters respectively as follows:

$$r = 6L,\ s = 1.75L \tag{2.18}$$

$$r = 6.1L,\ s = 5L \tag{2.19}$$

where the ship was moved from centre of the ellipse to ports side by a distance 0.75 L for head-on encounter situation. Figure 2.12 shows Coldwell's ship domain for head-on and overtaking encounters to clarify the shapes and distances of the domain.

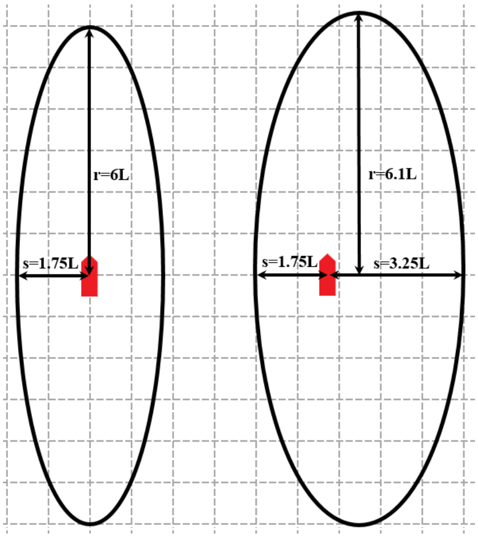

Figure 2.12 : Coldwell's domains for head-on and overtaking encounters.

Ship domain with its proposed different shape and size implementations is widely utilised for the purposes of navigational risk analysis, VTS planning, capacity estimation of waterways. In the literature, Three-Dimensional (3D) and Two-Dimensional (2D) domains are modelled. The 3D models also cover the draft and air draft of the ship. two-dimensional ship domains can be circular, elliptical, rectangular, hexagonal, polygonal and more complex shapes.

Zhao et al. (1993) proposed a fuzzy ship domain which is unlike the previous crisp domains and able to vary depending on domain violation (Jingsong et al., 1993). They mentioned about physiological basis of ship domain by the theory of proxemics. Moreover, related study is the first analysis-based one in the literature, as they conducted a critical analysis for domains of Fuji, Goodwin and Coldwell. Pros and cons of the previous domains were discussed and short solutions were proposed. Also they mentioned briefly about specs of a featured ship domain. James (1986) proposed a fuzzy logic based collision avoidance model which considers passing distance in fuzzy manner. Although Zhao proposed his model in a later time than James, Zhao's work was considered the first model of fuzzy domain because the James' model did not exactly correspond to the ship domain study.

Analytical solution based dynamical hexagonal ship domain for the purpose of path planning was proposed (Smierzchalski, 2000; Smierzchalski & Michalewicz, 2000; Śmierzchalski et al., 1999). Length and speed of OS and speed of TS were considered as the influencing factors of ship domain. They utilised radar data for their subsequent calculations of path planning, length of OS was used instead of TS' length.

Pietrzykowski (1999; 2001, 2008) determined a polygonal fuzzy ship domain for safety of navigation in restricted area and narrow fairway inspired by James and Zhao. Distance and bearing of the targets were included and fuzzy logic was implemented by navigators' opinions. Lately Pietrzykowski and Uriasz (2009) determined another polygonal fuzzy ship domain model to establish safety of navigation. CPA, distance, bearing and COG of TS were included for determining the distance of the domain.

Zhu et al. (2001) identified alike Goodwin's, two circular sectored ship domain by employing Back Propagation Neural Network (BPNN) which enables to eliminate complicated mathematical calculations for modelling of environment. Similar to Inoue (1981) length and width, block coefficient and rudder area of ships sub-criteria are considered to calculate effects of visibility and ship manoeuvrability.

Kijima and Furukawa (2003) proposed an analytical solution based elliptic watching and blocking areas for the purpose of determining the collision risk (Kijima & Furukawa, 2003). Concept of blocking area was inspired by precedent studies (Arimura et al., 1994; Fujii et al., 1966). The model assumes both of the OS and TS has their own watching and blocking areas. An overlap between watching area of TS and blocking area of OS indicates a risky condition and decision of evasive manoeuvre is to made. Length and breadth of ships, relative speed and relative angle of the encountered vessels were included as the influencing factors for distance of watching area. Blocking area was determined by considering length and breadth of ships. Domain overlapping is a triggering situation for collision avoidance manoeuvre in the proposed model.

A novel ship domain named as Fuzzy Quaternion Ship Domain (FQSD) was also proposed (Wang, 2010). Main purpose of the study was establishing safety of navigation. Speed, length, advance and tactical diameter of ship were the factors included in the model. Afterwards, he brought an innovation to to his quaternion ship domain by extending the factors: more detailed manoeuvrability of ship, navigator's state, visibility, wave, wind force and traffic congestion (N. Wang, 2012).

Hansen et al. (2013) proposed an empirical ship domain based on AIS data obtained for four-year period of Danish waters. They described their estimated domain as a minimum distance which navigators fell comfortable. The elliptic domain boundaries were determined according to no target should be entered principle. Shape of the domain was determined by visualising the distances of all ship encounters. All vessels were considered as OS one by one and the calculated distances were normalised with relevant ship's length. Determined distances of the domain are 4.5 ship lengths in ahead, 3.5 ship lengths in stern and 1.6 ships lengths in both sides.

A region based novel symmetrical polygonal ship domain was proposed for Thames River based on experts' opinion and local knowledge (Rawson et al., 2014). Data obtained from AIS was classified to investigate numbers of head-on, crossing and overtaking encounters. Since it has static and dynamic parts, it can be considered as a hybrid domain. As a result of expert consultation, distance of the domain was determined as 7 meters around the ships with a dynamic fore sector which was named as *"nose"*. Distance of the nose which was also influenced by manoeuvrability of the ship, was considered as a reaction distance and it was calculated by ship's steaming distance within 10 seconds. Collision risk was aimed to decide and domain overlapping was considered as a risky condition.

Another statistical analysis based, region specific polygonal ship domain was proposed for safety of navigation in Taiwan Island waters (Chang et al., 2014). According to the AIS information of 2009-2012 years, the CPA values of all vessels were examined. The ships with CPA values below 2 nm were considered and the ship domain was determined by utilising the local maximum method. Different encounter situations were also taken into account (head-on, crossing and overtaking). Central ship's circumference was divided into 16 sectors and the vessel densities were evaluated at every 22.5° angled sector.

Wang (2012) and Wang and Chin (2015) proposed an empirically calibrated asymmetrical polygonal ship domain by analytical formulation. The model assumes two diverse ship domain around the both OS and TS. The domain is modelled for confined waters and calibrated with real traffic data in Singapore Port and Singapore Strait for safety of navigation. It was modelled for head-on, crossing and overtaking encounters. Distance of domain boundary was calculated by including ships' length, speed, relative bearing and heading where shape was formed by joining the sequential vertices which were in their respective distances and clockwise angles.

Liu et al. (2015) proposed a model by calculating elliptic ship domain distance for the determination of traffic capacity according to the ship behaviour in restricted water channels. Arbitrarily, elliptic domain shape was chosen in the model which was inspired by Fuji's domain (Fuji & Tanaka, 1971). Navigating vessels along the channel, crossing vessels the channel, joining to another flow and turning were the categorised ship behaviours in restricted waters. For each behaviour situation, geometrical calculations based domain sizes were proposed taking ships' length, speed and width of the situation related channel into consideration. The model assumes that the domain OS is not violated.

Dinh and Im (2016) proposed quadrilateral blocking and circular action areas by combining both experts' opinion with analytical methods (Dinh & Im, 2016). The areas were modelled for only head-on situations. Action area is defined as an effective area to make evasive manoeuvre before the OS invades TS' blocking area. Length, advance distance of TS and GPS error in meter were the factors influencing the blocking area where action area was determined a multiplication of relative speed of the ships. Concept of the proposed model was inspired by Kijima's model (Kijima & Furukawa, 2003).

Szlapczynski and Szlapczynska (2016; 2017a) proposed a collision alert system based on domain violation of TS by OS. Analytic formulas were utilised for calculation of collision risk in the former study. Degree of Domain Violation (DDV) and Time to Domain Violation (TDV) factors were used to calculate degree of collision risk for any kind of ship domain. Although DDV was defined with degree term, risk level of collision and its alert category was determined based on a Boolean parameter that DDV is equal to zero or is greater than zero, so the term of degree does not define this factor correctly.

In the latter study, proposed DDV and TDV were utilised to define collision risk in the lights of International Maritime Organisation (IMO) Resolution MSC 252 (83*) "Adoption of the revised performance standards for Integrated Navigation System (INS)"* recommendations (IMO, 2007). They proposed three collision alert categories depending on the calculated degree of collision risk; Caution, Warning and Alarm. Each warning category was modelled in such a way that it provided appropriate warning according to the adversely determined DDV and TDV limit values.

Afterwards Szlapczynski et al. (2018a, 2018b) developed the aforementioned model for collision avoidance determination for the situations of give-way and stand-on.

The model covers encounter situations of head-on, crossing and overtaking. Algorithm firstly examines whether the domain is violated, then controls the visibility and encounter situation and finally determines the evasive manoeuvre by considering manoeuvrability of ship in detail. Domain overlapping is a triggering situation for collision avoidance manoeuvre in the proposed model.

Fan et al. (2018) proposed an early collision warning model for VTS operators based on analytically calculated elliptic ship domain (Fan et al., 2018). Encounter situations of head-on, crossing and overtaking were taken into consideration. Length, speed, draft and type of ships and visibility were considered as the factors influencing distance of domain boundary. According to the model, violation of either OS' or TS' domain is the situation triggering the warning system.

Zhou et al. (2018) proposed a novel approach to risk analysis of collision with a new ship domain concept. They brought a new criticism to the literature by expressing that in any encounter situation, OS and TS are need to be monitored and warned with same risk level of collision. For that respect, they were inspired by synergetic theory and employed this approach to Wang's (2010) quaternion domain (Wang, 2010). Speeds, lengths, breadths, advances and tactical diameters of two encountered ships factors were included to the calculations for all encounter situations.

Almost all of the 2D domains in the literature have been proposed for the purpose of determination of risk, capacity estimation, path planning and safety of navigation as collision oriented model. In addition to these studies, by considering two essential parameters of draft and air draft, some 3D domains have been proposed by employing similar shapes and methods with formers such as; analytical method, statistical analysis, expert consultation, fuzzy logic and artificial intelligence. Main difference between the concepts of 2D and 3D ship domain can be summarised as 3D domain concept considers two additional factors such as draft and air draft. With the 3D ship domain concept, it is observed that the domain concept is also being adapted for grounding. They have started to increase their popularity especially in recent years, but detailed approaches and solutions as much as 2D domains have not been developed yet (Chen et al., 2017). It should be noted that all domains can be converted to 3D domain by including draft and air draft factors (Pietrzykowski et al., 2018).

The essential issue is not to obtain depth and shallow contour information from the simulator or laboratory environment, but to develop some methods which are capable of analysing navigational risks for all waterways by directly obtaining data from electronic charts without any necessity of preliminary studies. It is assessed that analysed studies in the literature may not be fully capable to deal with this problem and provide a proper solution. It is also aimed to propose a solution approach to obtain necessary depth information from electronic charts.

Titles of the studies, and their researchers are expressed by letter code as shown in Table 2.3 for the purpose of using for subsequent table. Table 2.4 indicates summarization the ship domain studies investigated in this section, in terms of shapes, descriptions of ship domain, considered encounter situations (HO for head-on, CR for crossing and OT for overtaking), the methods for determining the ship domain, the factors involved in the calculation, the purposes of ship domain classifications and CRA.

Table 2.3 : Letter codes of ship domain studies.

Letter Code	Publishing Year	Name of Research	Researcher(s)
SD1	1971	Traffic capacity	Fuji & Tanaka
SD2	1975	A statistical study of ship domains	Goodwin
SD3	1977	A Model for calculating a maritime risk criterion number	Tak & Spaans
SD4	1980 - 1982	A computer simulation of marine traffic using domains and arenas - A computer simulation of multi-ship encounters	Davis et al.
SD5	1983	Marine traffic behaviour in restricted waters	Coldwell
SD6	1993	Comments on ship domains	Zhao
SD7	1999 - 2000	Domains of navigational objects as an aid to route planning in collision situation at sea, - Ships' domains as a collision risk at sea in the evolutionary trajectory planning	Smierzchalski
SD8	1999 - 2001 - 2008	Ship fuzzy domain in assessment of navigational safety in restricted areas - The analysis of a ship fuzzy domain in a restricted area - Ship's fuzzy domain – a criterion for navigational safety in narrow fairways	Pietrzykowski
SD9	2009	The ship domain–a criterion of navigational safety assessment in an open sea area	Pietrzykowski & Uriasz
SD10	2001	Domain and its model based on neural networks	Zhu et al.
SD11	2003	Automatic collision avoidance system using the concept of blocking area	Kijima & Furukawa
SD12	2010	An intelligent spatial collision risk based on the quaternion ship domain	Wang
SD13	2012	A novel analytical framework for dynamic quaternion ship domains	Wang
SD14	2013	Empirical ship domain based on AIS data	Hansen et al.
SD15	2014	Practical application of domain analysis: port of london case study	Rawson et al.
SD16	2014	AIS-based delineation and interpretation of ship domain models	Chang et al.
SD17	2012 - 2015	An empirical model of ship domain for navigation in restricted waters - An empirically-calibrated ship domain as a safety criterion for navigation in confined waters	Wang and Wang & Chin
SD18	2016	Dynamic ship domain models for capacity analysis of restricted water channels	Liu et al.
SD19	2016	The combination of analytical and statistical method to define polygonal ship domain and reflect human experiences in estimating dangerous area	Dinh & Im
SD20	2016 - 2017	An analysis of domain-based ship collision risk parameters - A framework of a ship domain-based collision alert system	Szlapczynski & Szlapczynska
SD21	2018 - 2018	A ship domain-based method of determining action distances for evasive manoeuvres in stand-on situations - Ship domain applied to determining distances for collision avoidance manoeuvres in give-way situations	Szlapczynski et al.
SD22	2018	Study on the early warning model of vts based on dynamic ship domain	Fan et al.
SD23	2018	Collision risk identification of autonomous ships based on the synergy ship domain	Zhou et al.

Table 2.4 : Summary of ship domain models.

Letter Code	Shape / Description	Encounter	Method	Factors	Purpose	CRA
SD1	Elliptic / b	NIL	Statistical analysis of radar data	Length	Capacity Estimation	NO
SD2	Three circular sectors / a	HO, CR, OT	Statistical analysis of radar data	LBP, GRT	Safety of Navigation	NO
SD3	Elliptic / a	HO, CR, OT	Analytical	Manoeuvrability, navigator's qualifications, psychological factors, reaction time, and environmental factor	Capacity Estimation	NO
SD4	Circular / a	HO, CR, OT	Computer simulation and expert consultation	Length	Safety of Navigation	NO
SD5	Elliptic / a	HO, OT	Statistical analysis of radar data	Length	Safety of navigation	NO
SD6	Three circular sectors / a	HO, CR, OT	Fuzzy logic	Nationality of ship personnel, size of ship, ship type, character of surrounding water, relative speed and traffic density.	Safety of navigation	NO
SD7	Hexagonal / c	HO, CR, OT	Analytical	Length and speed	Path planning	YES
SD8	Polygonal / a	NIL	Fuzzy logic	Range and relative bearing	Safety of navigation	NO
SD9	Polygonal / a	HO, CR, OT	ANN with fuzzy logic	CPA, distance, bearing and course of TS	Safety of navigation	YES
SD10	Two circular sectors / a	HO, CR, OT	BPNN	Length and breadth, block coefficient and rudder area of ships, visibility and ship manoeuvrability	Safety of navigation	NO
SD11	Elliptic / d	HO, CR, OT	Analytical	Length and breadth of ships, relative speed and relative angle between ships	Collision avoidance	YES
SD12	Quaternion / a	HO, CR, OT	Fuzzy logic	Speed, length, advance and tactical diameter of OS	Safety of navigation	NO
SD13	Quaternion / a	HO, CR, OT	Fuzzy logic	Speed, length, advance and tactical diameter of OS, navigators' state, visibility, wave, wind force and traffic congestion.	Safety of navigation	NO
SD14	Elliptic / c	NIL	Statistical analysis of AIS data	Length	Safety of navigation	NO
SD15	Polygonal / d	HO, CR, OT	Expert consultation	Speed and manoeuvrability	Risk estimation	NO
SD16	Polygonal / a	HO, CR, OT	Statistical analysis of AIS data	CPA, TCPA	Safety of navigation	NO
SD17	Polygonal / d	HO, CR, OT	Analytical	Ships' length, speed, relative bearing and heading	Safety of navigation	NO
SD18	Elliptic / a	NIL	Analytical	Ships' length, speed and width of the channel	Capacity Estimation	NO
SD19	Quadrilateral and circular / b	HO	Expert consultation and analytical	LBP, CPA, TCPA and GPS error	Collision avoidance	YES
SD20	Elliptic / b	HO, CR, OT	Analytical	Length	Risk estimation	YES
SD21	Elliptic / b	HO, CR, OT	Analytical	Length	Collision avoidance	YES
SD22	Elliptic / c	HO, CR, OT	Analytical	Length, speed, draft, type of ships and visibility	Risk estimation	YES
SD23	Quaternion / d	HO, CR, OT	Analytical	Speeds, lengths, breadths, advances and tactical diameters of two encountered ships	Risk estimation	YES

In this part of the thesis, a total of 51 models were examined in detail, their methods, the factors they included in the calculations, and the ways in which the problems were handled clearly. All models have also been evaluated in terms of whether they examine the risks of dynamic and real-time grounding and collision. The total number of convenient models for carrying out real-time risk analysis is 17 which constitutes 30% of all the models studied. Among these models, the proportion of models only focused on collision risk is quite high and their total number is 16, which corresponds to about 94%.

The number of models that dynamically address the calculation of both grounding and collision risk is only one (1) which corresponds about 6% of all models.

The most important reason of the above-mentioned problem is obtaining land and shallowness information from simulator environment or in environments created with many assumptions. In this thesis, shallowness information is obtained autonomously in real time by using Electronic Navigational Charts (ENC). All of the studies analyzed and the above-mentioned statistical information reveal the extent to which the subject and purpose of this thesis are tremendously novel.

3. DATA OBTAINING METHODS

In this section, we will discuss the methods of obtaining the data needed for grounding and collision risk calculations in the model. The aim of this section is to describe the methods of obtaining and processing data from real navigational bridge equipment of the algorithm that can analyse real-time navigational risks on bridge. The algorithm created in the scope of the thesis is written in C ++ environment with some required libraries, which is an object-oriented programming language for general purposes. C ++ is preferred as it is able to overcomes the tasks that need high processing power such as; fuzzy logic processes, calculating distances on the chart, bearing calculation, real-time display of many objects on the screen.

Data exchange and electronic connection between electronic equipment takes place within a standard. These standards, also referred to as data transfer protocols, allow the data generated and exported by a bridge equipment to be interpreted by other devices through appropriate connection and communication methods. NMEA protocol is the communication language used to communicate all bridge equipment. NMEA is a non-profit organisation consist of educational institutions, manufacturers, dealers and other stakeholders of marine electronic equipment affairs. Although NMEA-0183 protocol is widely used in marine equipment, the later version is NMEA-2000. In this thesis, data acquisition is modelled according to the most commonly used NMEA-0183 protocols on ships. Earlier versions, NMEA-0180 and NMEA-0182 were not used today, but were only slow data transfer protocols covering communication between Loran-C and autopilot equipment. NMEA-0183 was first released in March 1983 and has been updated several times with new versions. Table 3.1 shows the versions of the NMEA 0183 protocol that changed over time.

NMEA 0183 protocol which supports single talker and multiple-listener system uses simple American Standard Code for Information Interchange (ASCII) format for data communication and devices using this protocol are lined with serial connection. Whereas NMEA-2000, successor of NMEA-0183 protocol uses CAN (Controller Area Network) connection for data communication. Also it supports multi-talker and multi-listener data network capability with binary encoded message format.

Table 3.1 : Versions of NMEA 0183 protocol developed with time.

Version of NMEA-0183	Release Date
NMEA 2.00	January 1992
NMEA 2.01	August 1994
NMEA 2.10	October 1995
NMEA 2.20	January 1997
NMEA 2.30	March 1998
NMEA 3.00	July 2000
NMEA 3.01	January 2002
NMEA 4.00	November 2008

In the NMEA-0183 protocol, the data transfer takes place by means of standardized message formats produced by the sensor and the equipment. Each generated message starts with the "$" sign, followed by Talker ID (first two character) and "Type of Message" (last three character). They are followed by multiple data field codes separated by commas. Unlike the standard NMEA 0183 message sentences, the messages sent by the AIS device starts with the "!" sign. List of Talker IDs and Type of Message codes are given in Table 3.2 and Table 3.3 respectively (IMO, 2015). Optionally, the "*" symbol is used after the data fields and continues with the hexadecimal number so that the "Checksum, process is executed which is applied to control the data for errors that may occurred during communication or storage.

Table 3.2 : List of Talker IDs.

ID	Talking Equipment	ID	Talking Equipment
AG	Autopilot - General	IN	Integrated Navigation
AP	Autopilot - Magnetic	LC	Loran C
CD	Communications – Digital Selective Calling (DSC)	P	Proprietary Code
CR	Communications – Receiver / Beacon Receiver	RA	RADAR and/or ARPA
CS	Communications – Satellite	SD	Sounder, Depth
CT	Communications – Radio-Telephone (MF/HF)	SN	Electronic Positioning System, other/general
CV	Communications – Radio-Telephone (VHF)	SS	Sounder, Scanning
CX	Communications – Scanning Receiver	TI	Turn Rate Indicator
DF	Direction Finder	VD	Velocity Sensor, Doppler, other/general
EC	Electronic Chart Display & Information System	DM	Velocity Sensor, Speed Log, Water, Magnetic
EP	Emergency Position Indicating Radio Beacon (EPIRB)	VW	Velocity Sensor, Speed Log, Water, Mechanical
ER	Engine Room Monitoring Systems	WI	Weather Instruments
GP	GPS	YX	Transducer
HC	Heading – Magnetic Compass	ZA	Timekeeper – Atomic Clock
HE	Heading – North Seeking Gyro	ZC	Timekeeper – Chronometer
HN	Heading – Non North Seeking Gyro	ZQ	Timekeeper – Quartz
II	Integrated Instrumentation	ZV	Timekeeper – Radio Update

Table 3.3 : Type of Message codes.

Code	Messages	Code	Messages
AAM	Waypoint Arrival Alarm	MWV	Wind Speed and Angle
ALM	Almanac data	OSD	Own Ship Data
APA	Auto Pilot A sentence	RMA	Recommended Loran data
APB	Auto Pilot B sentence	RMB	Recommended navigation data for GPS
ASD	Autopilot System Data	RMC	Recommended minimum data for GPS
BEC	Bearing & Distance to Waypoint – Dead Reckoning	ROO	Waypoints in Active Route
BOD	Bearing Origin to Destination	ROT	Rate Of Turn
BWC	Bearing using Great Circle route	RPM	Revolutions
BWR	Bearing and Distance to Waypoint	RSA	Rudder Sensor Angle
BWW	Bearing – Waypoint to Waypoint	RSD	RADAR System Data
DBK	Depth Below Keel	RTE	Route message
DBS	Depth Below Surface	TLL	Target Latitude and Longitude
DBT	Depth Below Transducer	TRF	Transit Fix Data
DCN	Decca Position	STN	Multiple Data ID
DPT	Heading – Deviation & Variation	VBW	Dual Ground / Water Speed
DSC	Digital Selective Calling Information	VTG	Vector track an Speed over the Ground
DSE	Extended DSC	WCV	Waypoint closure velocity (Velocity Made Good)
DTM	Datum being used	WPL	Waypoint Location information
GGA	Fix information	XTC	Cross track error
GLL	Lat/Lon data	XTE	Measured cross track error
GRS	GPS Range Residuals	VDR	Set and Drift
GSA	Overall Satellite data	VHW	Water Speed and Heading
GST	GPS Pseudorange Noise Statistics	VLW	Distance Travelled through Water
GSV	Detailed Satellite data	VWR	Relative Wind Speed and Angle
HDG	Heading – Deviation & Variation	WDC	Distance to Waypoint – Great Circle
HDT	Heading – True	WDR	Distance to Waypoint – Rhumb Line
HSC	Heading Steering Command	WNC	Distance – Waypoint to Waypoint
MSK	Send control for a beacon receiver	WPL	Waypoint Location
MSS	Beacon receiver status information	XTE	Cross Track Error – Measured
MWD	Wind Direction & Speed	ZTG	Zulu time and time to go (to destination)
MTW	Water Temperature	ZDA	Date and Time

In order to provide real-time dynamic and static information to be needed for the calculations, all the message elements in the NMEA 0183 standard, which are given in Figure 3.1, have been introduced to the algorithm.

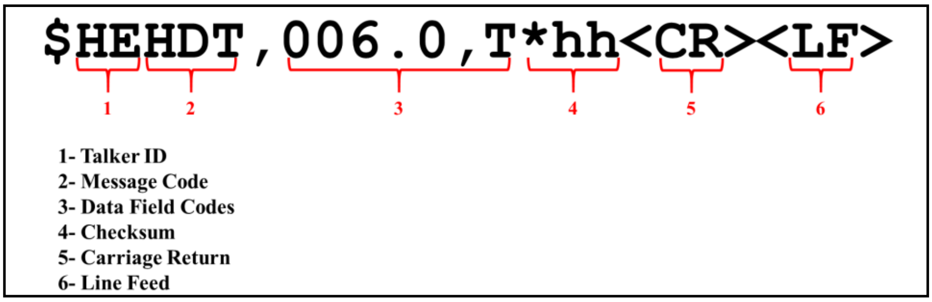

Figure 3.1 : Standard NMEA 0183 talker message.

In order to calculate the navigational risks, the dynamic data of own ship is obtained from the VDR which is bridge equipment, records many navigational data of not less than 12 hours. VDR performance standards was designed for ships in accordance with the International Convention for the Safety of Life at Sea (SOLAS) Chapter 5 (IMO, 1997). Data of date and time, position, speed, heading, Radar, AIS, ECDIS, VHF radio communications, order and feedback of rudder, engine order and feedback, thruster, main alarms, echo sounder, hull openings, status of watertight and fire doors, wind speed and direction are recorded by VDR.

In the algorithm, some input values obtained directly from sensors and information obtained by some required calculations. In Table 3.4, the classification of the information needed for the risks of collision and grounding is presented accordingly.

Table 3.4 : Inputs and their obtaining mechanism (IMO, 2015).

Data for OS	Remark	Data for TS	Remark
Position	Directly obtained from VDR	Position	Directly obtained from AIS by using VDR
SOG	Directly obtained from VDR	SOG	Directly obtained from AIS by using VDR
COG	Directly obtained from VDR	COG	Directly obtained from AIS by using VDR
Heading	Directly obtained from VDR	Heading	Directly obtained from AIS by using VDR
LOA	Indirectly obtained by Dimension Values	LOA	Indirectly obtained by Dimension Values
Breadth	Indirectly obtained by Dimension Values	Breadth	Indirectly obtained by Dimension Values
ROT	Directly obtained from VDR	ROT	Directly obtained from AIS by using VDR
Distance of Shallowness	Indirectly obtained by Haversine Formula	Distance from OS	Indirectly obtained by Haversine Formula
Bearing of Shallowness	Indirectly obtained by Haversine Formula	Bearing from OS	Indirectly obtained by Haversine Formula
Draft	Directly obtained from VDR	Relative Speed	Indirectly obtained by Haversine Formula
Type of Ship	Directly obtained from VDR	Draft	Directly obtained from AIS by using VDR
Dangerous Cargo Aboard	Directly obtained from VDR	Type of Ship	Directly obtained from AIS by using VDR
		Dangerous Cargo Aboard	Directly obtained from AIS by using VDR

For OS; Position, SOG and COG information are obtained directly from the GPS connected to the VDR. Heading information is obtained by the gyro compass sensor information connected to the VDR. There is no equipment to obtain LOA and Breadth information directly. This data are obtained as a result of a short mathematical process. Message sentences includes lateral and longitudinal distances of the ship's GPS antenna over the vessel which are sent by GPS and AIS. Using this information, LOA and Breadth information is obtained. According to SOLAS (1995) the ROT indicator is mandatory on ships with a capacity of 50,000 GRT and above, but is also frequently seen on even smaller ships (SOLAS, 1995). Therefore, as the sensor information can be obtained directly, if the sensor does not have this sensor information, ROT information is obtained by the mathematical process based on the Heading sensor information. Distance and Bearing of Shallowness information are obtained on the rhumb line principle after determining the shallow contour points as will be introduced in ENC Module. Since Draft information is one of Voyage Related data of AIS device, it is obtained directly via VDR. The type of ship information could be manually entered into the algorithm during the initial set-up of the algorithm for the OS. However, in order to eliminate the need to re-update the algorithm from the case of a change in the vessel type, this information is also obtained in the VDR device where the AIS information is sent. Type of Hazardous Cargo information, which is one of the AIS Voyage Related Data, is also obtained from the VDR device.

The data obtained for TS is as explained for OS. In addition to these, relative speed input is obtained by reading the speed information of TS in the AIS information through the VDR and performing vectorial operations with the speed information of the OS.

The algorithm created within the scope of the thesis is coded to be sub-modules running under the main modules and it is constantly exchanging data between the modules. There are 4 main modules created in the algorithm. These include AIS data obtaining module, ENC module, Calculation module and Visualization module. Detailed information about the main modules of the algorithm is presented in the ongoing section.

3.1 AIS Data Obtaining Module

SOLAS Chapter V, Regulation 19 determines carriage requirements of navigational equipment depending on vessel’s type and size. AIS carriage requirement is identified under SOLAS Chapter V, Regulation 19.2.4 which requires to carry AIS equipment on board all ships of 300 GT and upwards engaged international voyages and all passenger vessels regardless of size (IMO, 2001, 2015). Two different type of AIS is carried on board as Class A and Class B. The former one is used on board vessels of 300 GT and upward and the latter is low cost version that utilised by non-SOLAS or pleasure crafts with limited functions. Communication mechanism of AIS consist of one Very High Frequency (VHF) transmitter, two VHF receivers and one VHF Digital Selective Calling (DSC) receiver. The system has NMEA connections and interfaces with GPS, ECDIS, ARPA and Gyro for required dynamic data.

AIS is an automatic tracking system that enables to monitor other surrounding vessels carrying AIS on board and provides some navigational related information of them. Maritime traffic management can be conducted precisely and more safely than before by AIS as VTS stations can also utilise AIS equipment for monitoring vessels in vicinity and sending some safety related messages. AIS provides 4 different type of data as static information, dynamic information, voyage related information and safety related messages. Table 3.5 – Table 3.8 show all sub-data provided by AIS Class A (IMO, 2015).

Table 3.5 : Static information of AIS.

Static Information	General Information
IMO Number	Set on equipping.
Maritime Mobile Service Identity (MMSI) Number	Set on equipping. It shall be reset if ownership changes.
Call Sign and Name of Ship	Set on equipping. It shall be reset if ownership changes.
Type of Ship	Set on equipping. Selected from pre-determined type of ship list.
Length and Beam	Set on equipping.
Offset values of GPS antenna	Lateral and longitudinal distances over the ship. Set on equipping.

Table 3.6 : Dynamic information of AIS.

Dynamic Information	General Information
Navigation Status	It is to be manually selected from pre-defined list of status.
Position with Accuracy Indicator	Automatically fed by GPS. Accuracy information is for worse or better than 10 m.
Position Time Stamp in Coordinated Universal Time (UTC)	Automatically fed by GPS.
COG	Automatically fed by GPS.
SOG	Automatically fed by GPS.
Heading	Automatically fed by ship's Gyro.
ROT	Automatically fed by ship's Gyro.

Table 3.7 : Voyage related information of AIS.

Voyage Related Information	General Information
Draft	Entered manually prior to each voyage. Deepest draft is to be set.
Type of Hazardous Cargo	It is to be manually selected from pre-defined list of hazardous cargo.
Destination and ETA	Entered manually prior to each voyage. When necessary, updated appropriately.
Waypoints (Route Plan)	Entered manually prior to each voyage.

Table 3.8 : Safety related messages of AIS.

Safety Related Messages	General Information
Short Safety Related Messages	A free format text is typed manually

Depending on AIS Class, type of information and sub-data of dynamic information such as ship's navigational status, speed and course alteration, AIS sends data with different sending frequency. For example, voyage related and static information are sent automatically in every 6 minutes or on request from other AIS. Safety related messages are sent when it is required. Table 3.9 shows multi-parameter based dynamic data sending intervals of AIS Class A in detail (IMO, 2015).

Table 3.9 : Data sending frequency of AIS Class A.

Status of Ship	Data Sending Interval
Ship moored or at anchor and not faster than 3 knots	3 minutes
Ship moored or at anchor and faster than 3 knots	10 seconds
Ship speed between 0 and 14 knots	10 seconds
Ship speed between 0 and 14 knots and altering course	3.3 seconds
Ship speed between 14 and 23 knots	6 seconds
Ship speed between 14 and 23 knots and altering course	2 seconds
Ship speed more than 23 knots	2 seconds
Ship speed more than 23 knots and altering course	2 seconds

As the frequency of sending AIS data are examined, it is obviously appropriate bridge equipment for calculating real-time navigation risks.

The basic steps of the AIS data obtaining process can be listed as obtaining data in NMEA format, AIS parsing, identifying message types, eliminating redundant message types and interpretation of required data. Flowchart of the data obtaining process is given in Figure 3.2.

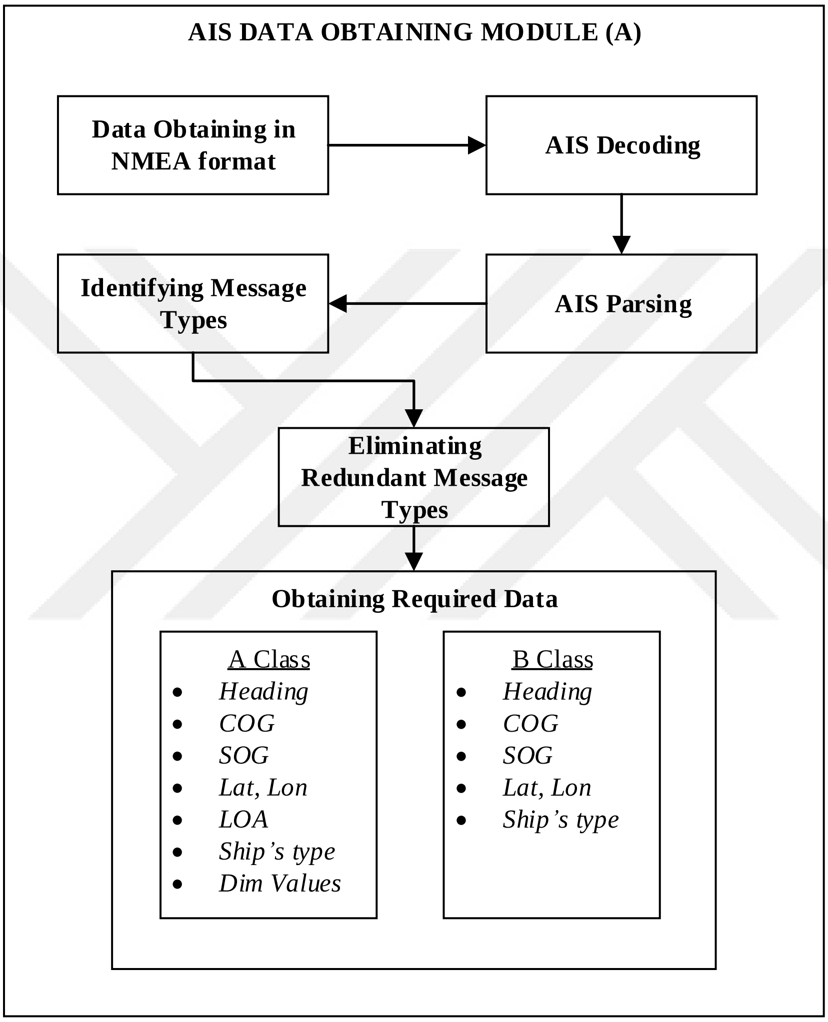

Figure 3.2 : Flowchart of AIS data obtaining process.

AIS message sentences unlike standard NMEA 0183 messages starts with the "!" sign. If the sending station is a ship, it is usually the message that starts with! AIVDM or! AIVDO. Former one indicates a message from any target ship and the latter one shows a message generated by own ship's AIS device. AIS messages are specially configured to send the maximum data in the smallest possible size. AIS message sentences of up to 82 characters are encoded in 6-bit ASCII. Figure 3.3 shows a received but not decoded sample of an AIS message sentence.

```
!AIVDM,1,1,,A,1:0Gph001O24fcHGMeH79Uap0hJa,0*69
```

Figure 3.3 : Sample of a received AIS message sentence.

As with the standard NMEA 0183 message sentences, the sentences that begin with the Talker ID will continue with the number of sentences, sentence number, message ID for sequential messages, class of AIS, content of message which is named as data payload, and checksum.

AIS is the equipment used to monitor and make safer the maritime traffic and is used not only by ships but also by many coast stations, VTS stations and Aids to Navigation (AtoN). Therefore, the part of Talker ID differs depending on the type of message sending station. Table 3.10 provides a list of other Talker IDs except own ship and target ship.

Table 3.10 : List of Talker IDs.

Talker ID	Talker	Talker ID	Talker
!AB	AIS Base Station	!AS	Limited Base Station
!AD	Dependent AIS Base Station	!AT	Transmitting Station
!AI	Mobile Station	!AX	Repeater Station
!AN	Aid to Navigation	!BS	Deprecated Base Station
!AR	Receiving Station	!SA	Physical Shore Station

AIS messages are sent periodically at certain time intervals, when requesting information from another device, or manually. The information contained in the messages are classified according to their subject and standardized with the International Telecommunication Union 1371 (ITU) standard (ITU, 1998). Accordingly, a total number of 27 message types were determined. In each message type, sentences with different information are produced and the decoding process varies for all message types. Table 3.11 shows the list of AIS message types. As the information needed for the thesis can be provided by reading the message types 01, 02, 03, 05, 18 and 24, the parsing coding of the other message types has not been performed.

Table 3.11 : Standard message types of AIS.

Number	Message Type	Number	Message Type
01	Class A Position Report	15	Interrogation
02	Class A Position Report (Scheduled)	16	Assignment Mode Command
03	Class A Position Report (Response)	17	DGNSS Binary Broadcast Message
04	Base Station Report	18	Standard Class B CS Position Report
05	Static and Voyage Related Data	19	Extended Class B Equipment Position Report
06	Binary Addressed Data	20	Data Link Management
07	Binary Acknowledge	21	Aid-to-Navigation Report
08	Binary Broadcast Message	22	Channel Management
09	Standard SAR Aircraft Position Report	23	Group Assignment Command
10	UTC and Date Inquiry	24	Static Data Report
11	UTC and Date Response	25	Single Slot Binary Message
12	Addressed Safety Related Message	26	Multiple Slot Binary Message with Communications State
13	Safety Related Acknowledgement	27	Position Report for Long-Range Applications
14	Safety Related Broadcast Message		

Message types of 01, 02, and 03 have a common sentence and content structure including navigational information and thus they are called Common Navigation Block (CNB) (Koto, 2018). Even though the reasons of sending are different, their content is the same and the unique type of message used to obtain the dynamic data of the ships. It occupies total of 168 bits.

The interpretation of the AIS message sentences is carried out in two main stages. In the first stage, AIS message sentences are decoded with ASCII 6-bit which is a typical character encoding measure that can encode only 64 distinct character. In the second stage, the resulting binary data are converted to decimal and the parsing of the AIS messages is completed. At this stage, according to each type of message, knowledge of which information contained in which digit is added to the algorithm. In this way, all number of 01, 02, 03, 05, 18 and 24 messages are converted into data for use. The decoding process of the AIS message shown in Figure 3.3 which is described in the following section. The main parts of the received AIS message shown in Figure 3.4.

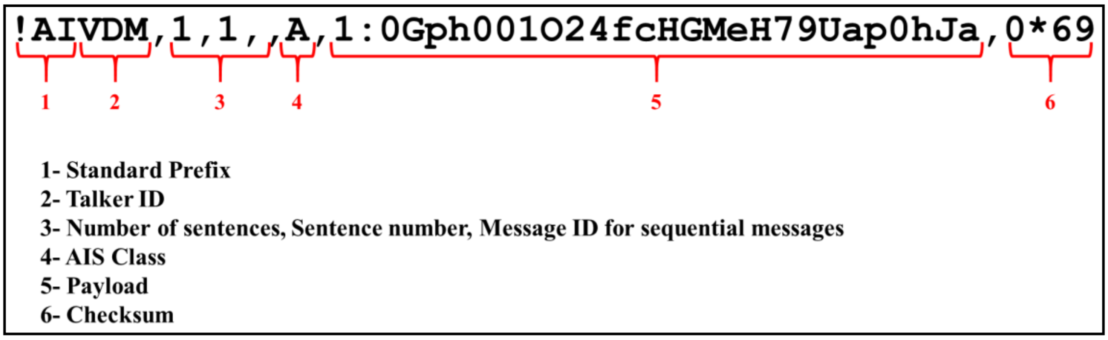

Figure 3.4 : Main parts of a received AIS message sentence.

Lookup tables, which are utilised for parsing the digit of payload parts in static and voyage related messages are added to algorithm. As an example, lookup table of digit fields for CNB is given in Table 3.12. Figure 3.5 indicates ASCII 6-bit version of the payload which is colourized based on distinct digit fields of navigational dynamic information.

Table 3.12 : Lookup table of digit fields for CNB.

Field	Len	Message Type
0-5	6	Message Type
6-7	2	Repeat Indicator
8-37	30	MMSI
38-41	4	Navigational Status
42-49	8	ROT
50-59	10	SOG
60-60	1	Position Accuracy
61-88	28	Longitude
89-115	27	Latitude
116-127	12	COG
128-136	9	Heading
137-142	6	Time Indicator
143-144	2	Indicator of Manoeuvre
145-147	3	Spare
148-148	1	Receiver Autonomous Integrity Monitoring (RAIM) Flag
149-167	19	Radio Status

Figure 3.5 indicates ASCII 6-bit version of the message which is colourized based on distinct digit fields of navigational dynamic information.

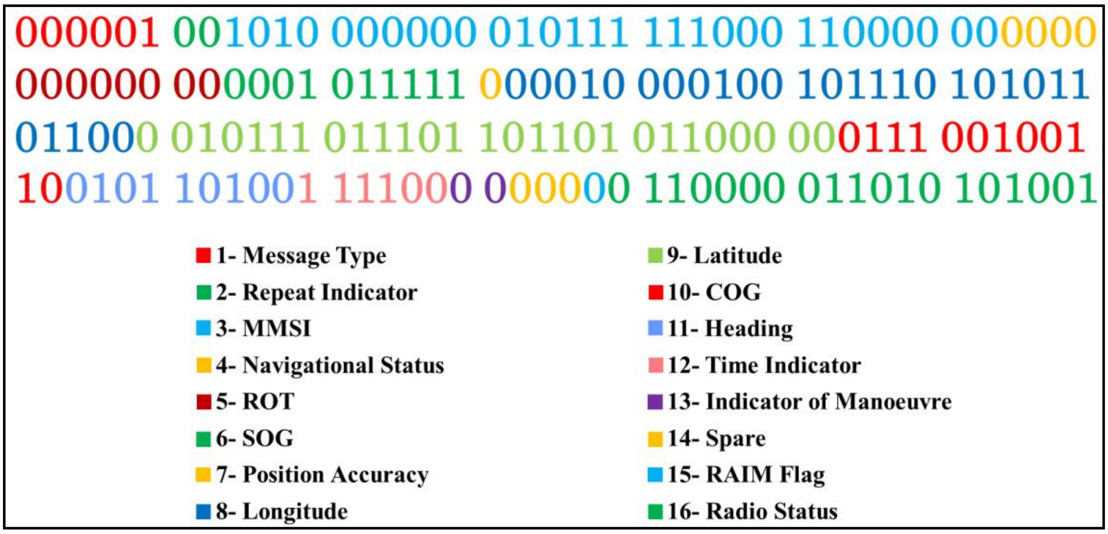

Figure 3.5 : Colourized ASCII 6-bit version of the payload.

When the sample message given in Figure 3.5 of a real ship passing through Istanbul Strait is decoded, it is interpreted that Navigational status is under way using engine, MMSI number is 671480000, COG is 183 °, Heading is 180 ° and 9.5 knot speed.

Binary ASCII 6-bit data are subjected to one more conversion from binary to decimal.

There are some important points listed below which should be considered when evaluating the decimals obtained after this conversion;

- ROT value of AIS is encoded between 0 and 708 degree/min. Multiplication result of the square root of the ROT sensor value by 4.733 is sent via AIS message. Therefore, the square of the number obtained by parsing process is multiplied by 4.733.
- SOG is a value between 0 and 102 knots which is formed of 0.1 decimal. Value obtained by parsing process is multiplied by 0.1.
- Position accuracy indicator can have a value of 1 and 0 which shows position accuracy of less than 10 meters and more than 10 meters respectively.
- Latitude and Longitude are given in 1/10000 minutes and therefore, obtained values are multiplied by 600,000. Calculated values are in degree and in case of requirement they are to be converted into degree, minute, second format.
- COG is a value between 0 and 3600 which is formed of 0.1 decimal. Value obtained by parsing process is multiplied by 0.1.

As a result of all these operations, Heading, COG, SOG, Latitude, Longitude, Ships Type, Dimension Values information is obtained and these processes are repeated in real time. The vessel information obtained is stored in the Ship Container section of the algorithm according to the MMSI numbers of ships. As the AIS messages arrive, the information in the corresponding MMSI in Ship Container is updated according to the content of the incoming message. The information generated in the AIS data Obtaining Module is sent to other modules in the algorithm. AIS data acquisition module has a one-way data communication between the others. Collision risk calculation inputs CPA, TCPA, Bearing, Relative Direction and Relative Speed data are sent to Calculation Module for risk computations.

3.2 ENC Module

ENCs are electronic charts used in ECDIS and produced depending on official charts and source of official hydrographic offices which are updated, coded and fulfilled in accordance with international standards. International Hydrographic Organization (IHO) developed some standards to ensure secure, accurate and interpretable standard of ENCs. Standards of S-52, S-57, S-58, S-62, S-63 are directly ENC related standards developed by IHO (IHO, 2017).

S-52, *"Specifications for Chart Content and Display Aspects of ECDIS"* is the standard on ECDIS display aspects. Lines, points, symbols, colours any any other visual objects are standardised by S-52 that means any kind of approved type ECDIS user monitors same visualisation objects. Presentation library 4.0 it the latest version of S-52 released by IHO since 31 August 2017 (IHO, 2017).

S-57, *"IHO Transfer Standard for Digital Hydrographic Data"* is the standard of data format developed for standardisation on transferring digital hydrographic information between any kind of stakeholders including end users.

By means of S-57, all information of ENCs is guaranteed to be interpreted by each stakeholder for safe navigation.

S-58, *"Recommended ENC Validation Checks"* is validation and check standard for hydrographic offices includes a series tests prior to release of ENCs. It ensures the ENCs are malfunction-free on display and any kind of data interpretation.

S-62, *"ENC Producer Codes"* was firstly released in 1996 as an annex to S-57 standard. Later on requirement of more frequent revision caused to publish a stand-alone IHO publication (IHO, 2019). It includes code list of all producing agencies.

S-63, *"IHO Data Protection Scheme"* is one of the latest released standard to ensure protection to piracy, restricted access which provides access by only approved users with licence, and authentication which guarantees the ENC is obtained from approved providers. Prior to release of S-63, any kind of ENC can be included any ECDIS in case of having licence for related ENC. The S-63 standard prevents this mentioned application, and the ENC does not operate if the user code and the ECDIS equipment code do not match even if the user has a license to use it (IMO, 2017).

Due to the lack of an ECDIS equipment to be approved by the IHO within the scope of the thesis, the acquisition of data from ENCs was carried out with the ENCs of S-57 standard, which are not encrypted with the S-63 standard.

In the scope of the thesis, chart information is needed due to the demand for depth and land information in calculating the risk of grounding. Chart information can be obtained by some distinct method for only non-dynamic systems. It can be obtained from simulator environment, by using special methods and for specific areas from ECDIS, and even from paper charts. However, none of these methods can be integrated into a system that can run on-board ship. Also the depth of shallowness is dynamically dependent on the ship's voyages, in other words it depends on the ship's load condition. For example, in a ballast condition of a 160,000 DWT tanker and in a fully loaded condition of it, the difference in draft is about 7.5 meters (Transas, 2012). In cases where that condition is not taken into account, it is not possible to mention about the realism of an algorithm, no matter how strong the risk calculations are employed in terms of academic and methodological perspective.

Standard S-57 electronic chart is a vector format based on the standard of S-57 object model which describe hydrographic data as a combination of spatial and descriptive characteristics. All of 280 objects of S-57 charts have two main parts as features and spatial parts. The feature part contains descriptive attributes without any geometrical information, whereas spatial part contains geometrical data of type vector and some additional descriptive features.

In other words, chart objects contain descriptors (attributes) under the features of a specific object that specify the boundaries of name, scale, datum, latitude and longitude. In addition, there exist geometric layers (spatial parts) such as area, line string, point, polygon that describe geometric features of objects.

Chart reading is performed by a node called *Chart Reader*, evaluating each object in the form of layers. For example, the land object is named as LNDARE (land area) and according to the attributes such as CONDTN (condition), NOBJNM (object name in national language), OBJNAM (individual name of object) and geometric attributes such as area, line string, point, polygon, the object properties are detected by the model. This process is executed separately for all S-57 charts and the objects they contain. The model creates a chart object using layers, attributes, and features by reading the S-57 files in the specified file locations from the file system using the Geospatial Data Abstraction Library (GDAL) which is a reading and mapping software application. It then adds the created chart object to the program's *Chart Container* object. In order to simplify the process of drawing geometric properties, these geometric properties are converted to Mercator transformations in a separate array in Calculation Module while reading the chart files. Table 3.13 shows used types of the chart objects for the model.

Table 3.13 : Chart objects utilised in the model.

Chart Objects		
Beacon, isolated danger	Buoy, special purpose general	Hulk
Beacon, lateral	Cable, overhead	Land area
Beacon, safe water	Canal	Pylon/bridge support
Beacon, special purpose general	Caution area	Quality of data
Bridge	Coastline	Restricted area
Buoy, cardinal	Coverage	Sea area
Buoy, isolated danger	Depth area	Sounding
Buoy, lateral	Depth contour	Survey reliability
Buoy, safe water	Harbour facility	Wreck

Figure 3.6 shows main stages and sub-modules of ENC reading process of ENC Module.

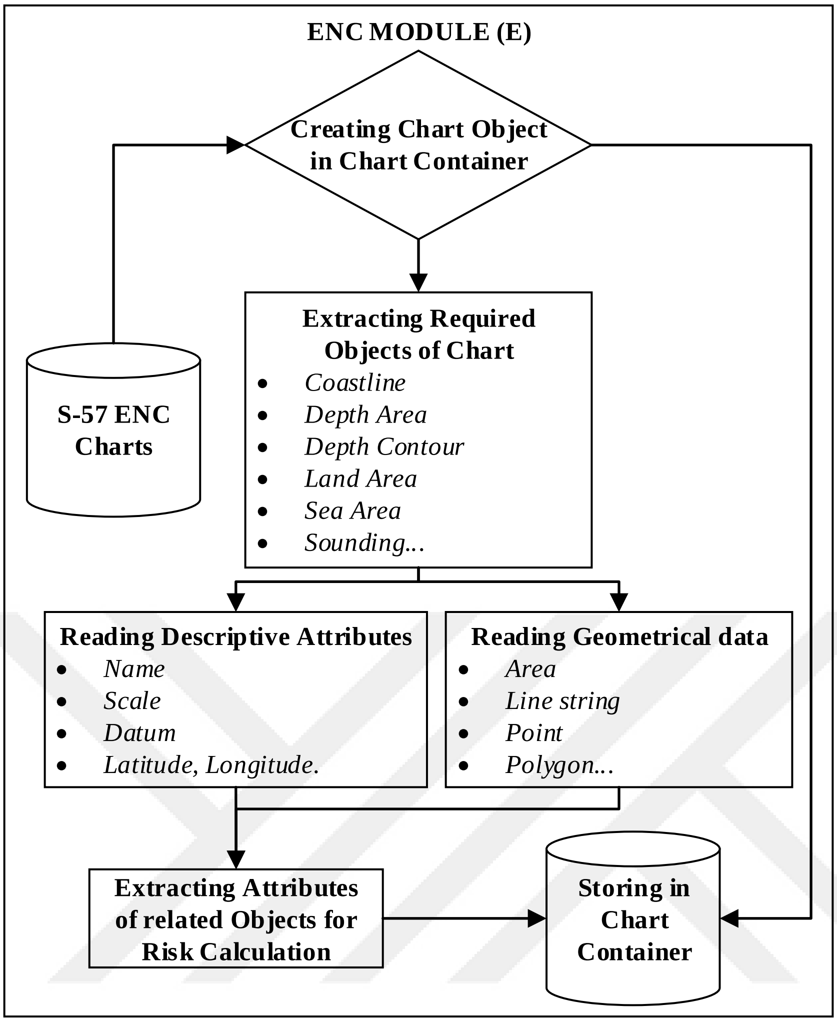

Figure 3.6 : Flowchart of ENC reading process.

Within the scope of the thesis, considering the position of own ship on ENCs, surrounding depth points, depth areas and depth contours are determined. The position information of the depth contour created by a set of depth points that may cause a grounding risk is sent to Calculation Module for the purpose of real-time calculation of the distance, bearing, CPA and TCPA of the points between shallow contour and ship. Contours such as 0, 5, 10, 20, 30, 50 meters, which are available by default in ENCs, do not always meet the required depth information based on the ship's actual draft. The depth information in especially indicating coasts of U.K. ENCs with GB code can be more detailed in terms of depth information, but it is often not possible to find the operationally required depth information. Standard ECDIS does not have the ability to obtain new depth points that are not found in the default ENC library by processing the depth information in the ENC as in the algorithm of this thesis. In order to overcome this problem, high order linear interpolation is made by Calculation Module to obtain the required intermediate depth values which are not available even in the standard ECDIS. For this purpose, firstly, all depth points within the ENC were read, recorded with their positions to the array list and interpolated between the closest depth points for the required intermediate depth points, which is executed in the Calculation Module. Depending on the own ship's speed, the entire circumference of the ship is scanned for 360 degrees at intervals of 1% of 1 degree at a distance of 1-hour range. The nearest deeper and shallower points are detected with their positions and depth information which are already available with ENC, and a high-grade linear interpolation process is performed for the required depth information. Thus, the depth points that will be dangerous for the ship navigation are determined together with their positions in order to carry out the calculations of grounding risk. Computed results are sent to the Visualization Module to indicate the obtained new shallow contour and stored in memory as a set of points with a distance of 10 meters between each other's. Figure 3.7 shows computed multi-point shallow contour with a distance of 10 meters between each point.

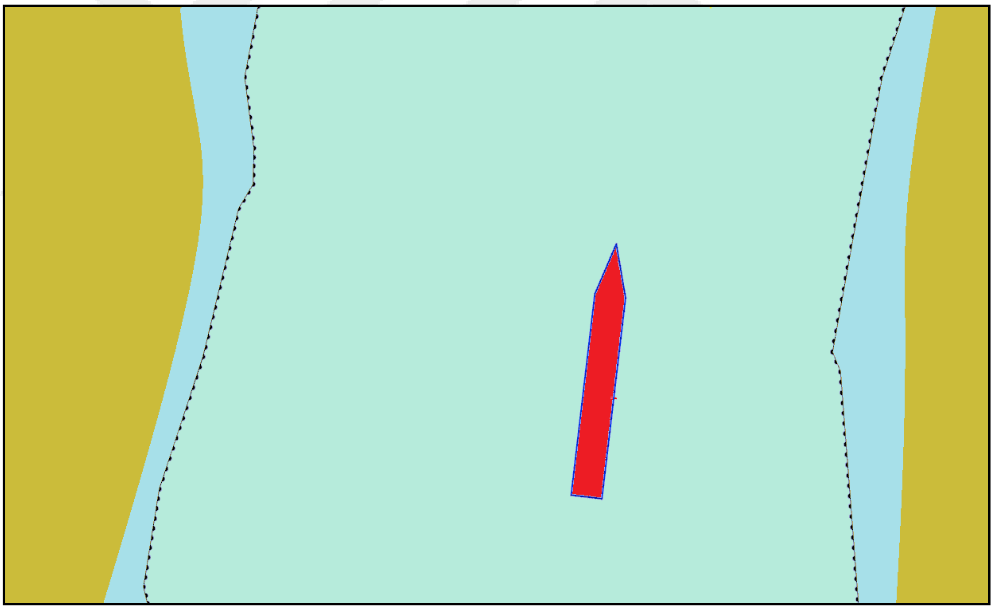

Figure 3.7 : Computed multi-point shallow contour.

3.3 Computation Module

This part of the algorithm is the module that the most intense data exchanges is performed with other modules. The parsed or interpreted raw data through other modules is sent to the Computation Module and made into inputs to be used in risk calculations. This module, which is the heart of the algorithm, has many sub-modules and is the part that sends data to other modules by doing different calculations, but also processes new data obtained from them. Latitude and longitude transformation for distance and bearing calculations, depth interpolation for the demanded depth value that is not included in standard S-57 charts, determination of distance between sequential depth points and their positions, position and interval determination of multi-point ship forms, computation of individual linear velocity of each determined ship points, relative speed, CPA, TCPA calculations are conducted by Computation Module. Figure 3.8 shows main stages and sub-modules of whole process of the module.

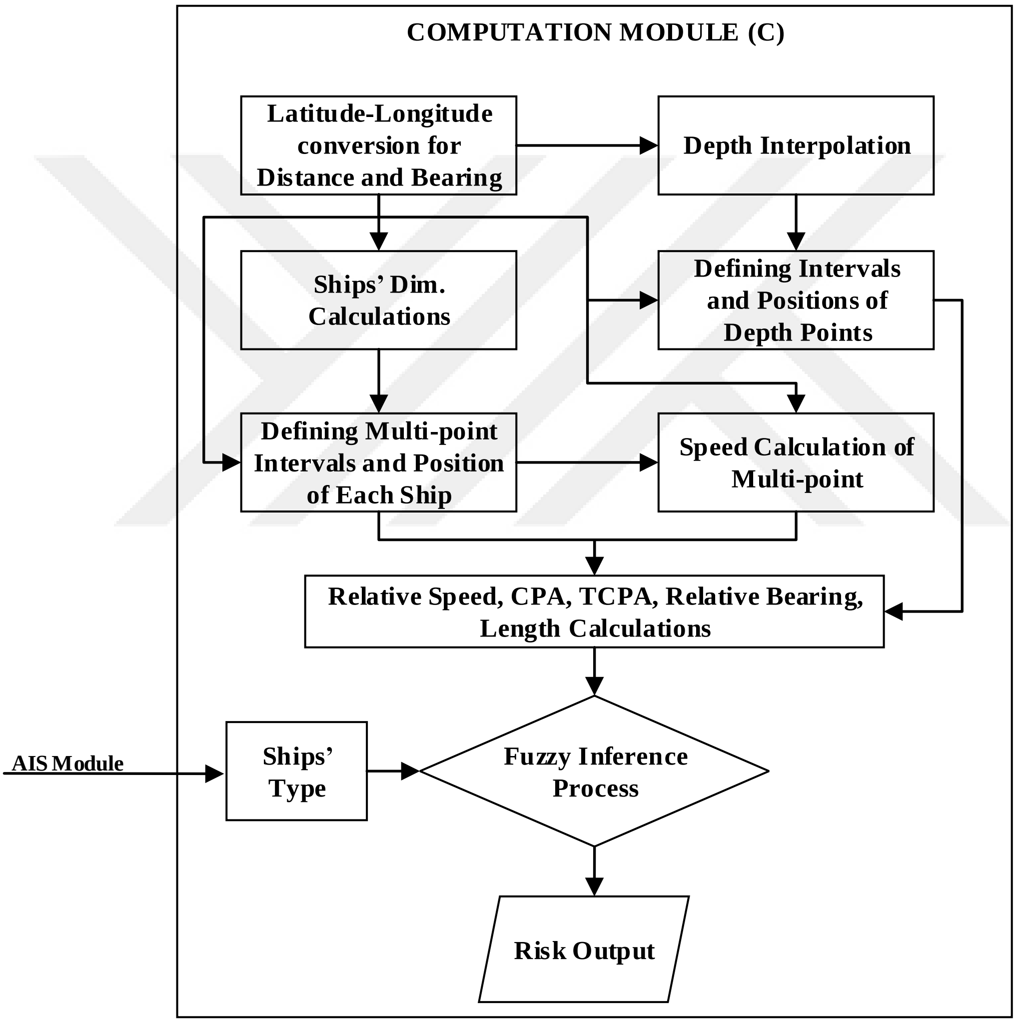

Figure 3.8 : Flowchart of calculating process.

The distance is the first and the most important input at every stage of the calculations made in the algorithm. It is a primary process for determining follows; the distance between the points, LOA and breadth determination of ships, creating ship multi-points, relationship between OS points and TS points, creating shallow contour multi-points, relationship between OS points and shallow contour points, and indirectly for calculating CPA, TCPA and bearing. These operations are performed in latitude-longitude conversion sub-module.

Over the ship's dimension value calculation sub-module, the lateral and longitudinal offset values of the GPS antenna are determined and positioned so that the LOA, width information of the vessel is obtained. In addition, this calculation is of great importance in terms of drawing 2D ship form and accurate detection of ship multi-point positions by the algorithm. Dimension values are sent by AIS in a sequence of distances to bow, stern, port and starboard. Distances are given in meters. Figure 3.9 indicates an example of Dimension Values over a ship form.

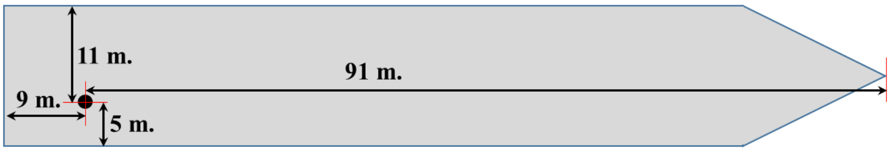

Figure 3.9 : Indication of dimension values over a ship.

The algorithm perceives that the full length of the ship is 100 meters and its width is 16 meters. This is done only once for all ships in the Calculation Module and is saved in the stored list of ship properties with their MMSI numbers.

In the literature, similar studies consider the own and target ships as a single-point object for risk calculation. (Bukhari et al., 2013; Chen et al., 2014; Kijima & Furukawa, 2001; Pratiwi et al., 2017). However, in this study, the own ships and the target vessels were considered as multi-point and the calculations were carried out accordingly. In other words, own ship and target ships are drawn depending their actual dimensions in the light of the information obtained from bridge equipment in NMEA 0183 standard and AIS respectively. They are formed as a cluster of points on the outer boundary of ships' form with a distance of 10 meters. Multi-pointed form of the ship given in Figure 3.9 is indicated in Figure 3.10.

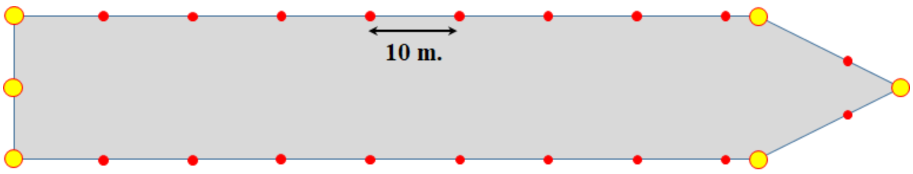

Figure 3.10 : Indication of multi-point ship form.

As it is seen, while creating the multi-point ship form, the regions that are considered critical for the ship form (marked with yellow points) are first pointed out in the multi-point determination process. Point positioning is then carried out from head to stern, initiating from the starboard side. Even if the width of the ship is not suitable for positioning another point on the stern section, an additional point is placed in the exact centre part. Afterwards, the process of positioning the points towards the head section continues with intervals of 10 meters from both sides of the ship (port and starboard). Port and starboard bow sections, and the extreme end of the ship are also important areas, and in any case, a point is placed to there. For these located points on the ship form, an array list containing their distance and bearing information from the GPS antenna is created and depending on the movement of the ship, the positions, linear velocity and COG information of all these points are calculated instantly in the latitude-longitude sub-module and sent to the CPA-TCPA sub-module, another sub-module of the Calculation Module, to convert them to the input values required for risk calculations.

Similarly, an array list containing location information is created for the 10 meter spaced points placed on the determined shallow contour and sent to the CPA-TCPA sub-module for necessary calculations. All points on the shallow contour within 1-hour distance considering the ship's speed, are taken into account. In this context, depending on the movement of the ship, the shallowness in the range of 1-hour change at any time and all these calculations are made repeatedly in real time.

In this way, real-time continuous risk calculations can be made between all the points on the ship and on the shallow contour. The obtained instant highest risk value is used to generate the risk graph. Calculated shallow contour and shape of own ship in multi-points form are given in Figure 3.11.

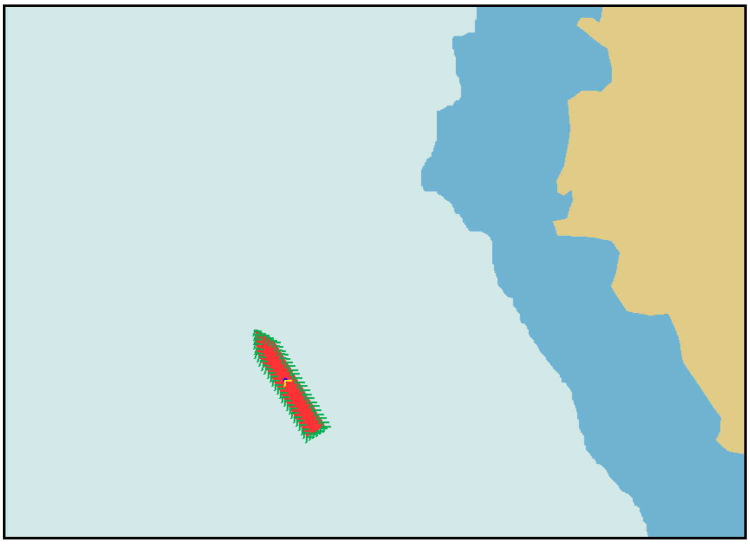

Figure 3.11 : Calculated shallow contour and multi-point ship form.

Relative bearing, relative speed, CPA and TCPA which are inputs for risk calculations and obtained by a series of computations are calculated in the latitude-longitude conversion and CPA-TCPA sub-modules respectively for both target ships and shallow points.

3.4 Visualization Module

This module is the centre where all perceived and calculated data are sent and converted to visual output. Data decoded and parsed by AIS module, S-57 chart data read by the ENC module, distance, relative bearing, relative speed, CPA, TCPA, multi-point ship form and dimensions data computed by Calculation Module are visualised in this module. Also data that subjected to methodological evaluation process are sent to Visualisation Module to provide result representations and suitable visual output. Information received from all other modules is finalized in this centre with a user-friendly interface. The layer method applied in the visualization of S-57 charts was also applied in the visualization of all data. The user interface has visualized with S-57 charts on the bottom layer, symbols scaled to the actual dimensions of the ships on the middle layer, and risk indicators on the top layer.

In addition, in this module, functions that may be needed during operational use are provided to be visualized. Data movements that may be required according to user inputs are also made by sending them to the relevant modules from Visualization Module. Figure 3.12 shows entire visualization process and its sub-modules.

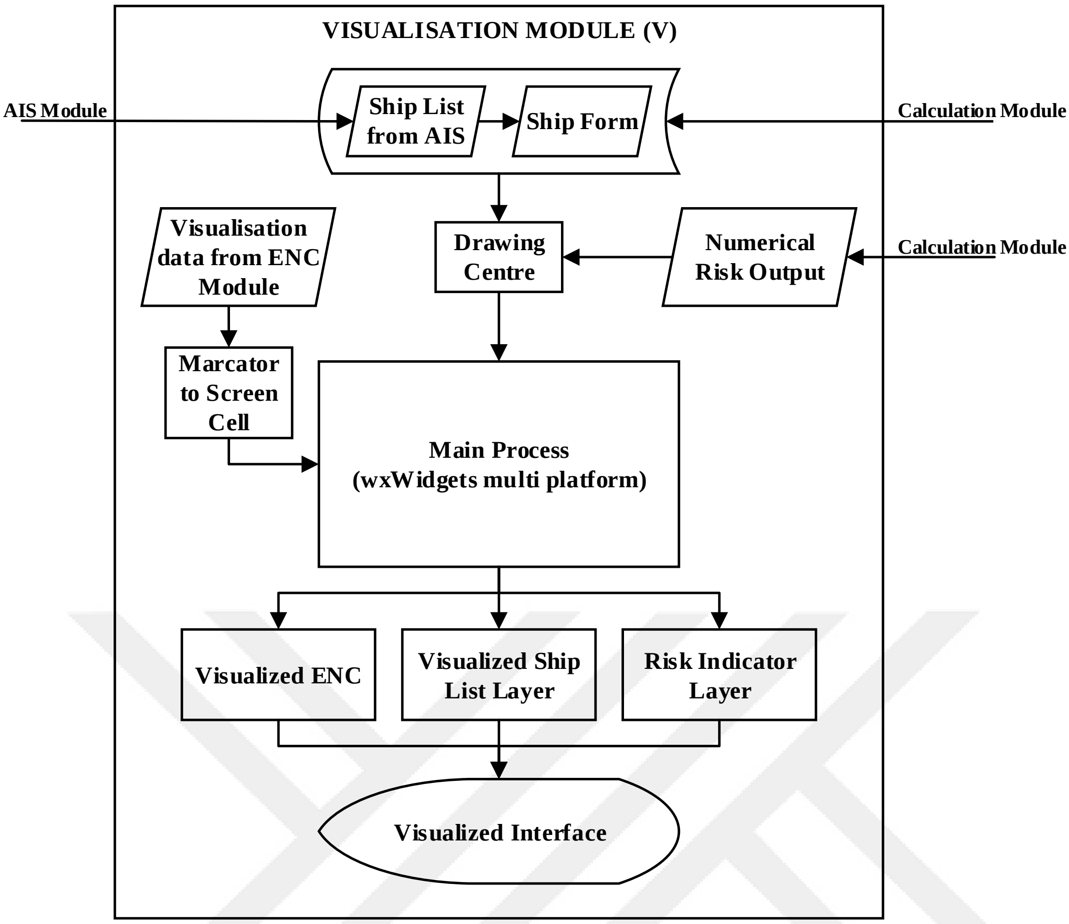

Figure 3.12 : Flowchart of visualization process.

The main visualization centre (main process), the heart of the visualization module, uses the wxWidgets multi-platform library, which can be accessed as an open source on the C++ platform. This is the centre where S-57, AIS and risk indicator layers are rendered and visualized. Prior to this centre, the Drawing Centre, where the ship forms were drawn, was created where graphical drawings of the target ships are carried out in accordance with their real dimensions by using AIS data.

In order to transfer the chart layout to the screen image, it is extremely important that locations of objects are determined and positioned correctly. For this purpose, the position transformation of the chart objects on the screen are carried out for all objects whose Mercator projection position conversions were made earlier. First, the positions of the upper left and lower right corner points of the area covered by the screen are calculated and cellular position conversions of the Latitude-Longitude positions on the 256*256 screen size are performed. After the Latitude-Longitude to screen cell transformation of all charts and objects with latitude and longitude information, it is decided whether the map and objects will remain in the area shown by the screen, and whether the map and object will be displayed accordingly. Chart objects are visualized by a laminar structure created with sea bottom with land borders, water level objects and surface objects respectively from bottom to top where GDAL library was used to visualize the S-57. The main layers used for chart drawing within the scope of the model are DEPARE, DEPCNT, LNDARE, SEAARE AND SOUNDG. Figure 3.13 shows the standardized version of an S-57 chart, which has been vectorised in the ENC module, with GDAL applications.

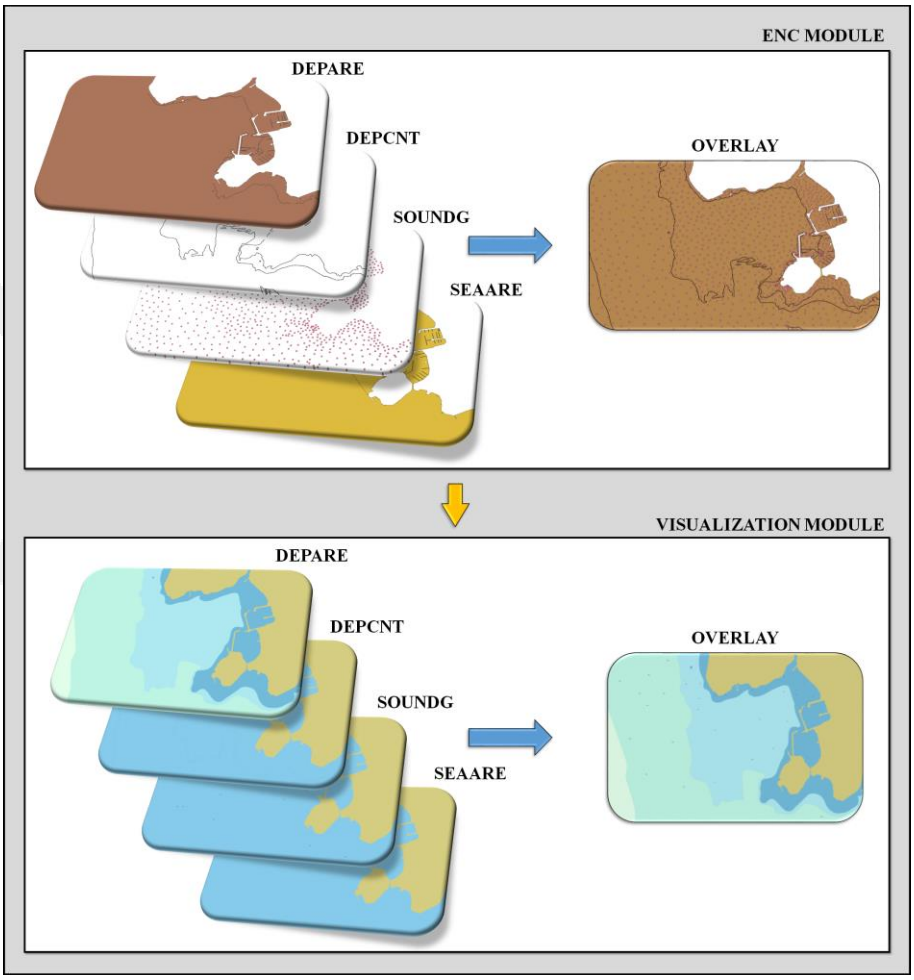

Figure 3.13 : Visualized S-57 with GDAL standard.

After completing the pars and decode operations in AIS Module, the target ship information is sent to the Calculation Module for the mathematical formation of multi-point ship shapes. After the ship forms are calculated, they are forwarded to the Visualization Module for visualization. All ship data, which is sized in accordance with the ship dimensions and created visual graphics in the drawing centre, is transmitted to the Main Process in which wxWidget multi-platform library is utilised for visualisation.

The risk calculations performed in the Calculation module are displayed in the model interface on the top layer. The numerical risk results sent to the Drawing Centre are plotted here and sent to the Main Process sub-module.

The shallowness, coastline, floating targets and target ships that cause instant risk result are coloured green yellow and red according to their risk levels. A ring shown around ship symbols is coloured according to the risk colour they have for the own ship. In addition, the shallow contour information obtained by interpolating in the calculation module is coloured according to the risk degree they have with an interval of 10 meters. By default, the highest risk value of collision and grounding during the navigation of own ship, which is named as resultant risk is constantly displayed in a risk monitoring window positioned at the bottom right of the screen. This window shows the risk value, distance of the target causing the risk, CPA, TCPA and bearing information. Depending on the type and level of the risk, it is aimed to attract the attention of the user by flashing the red coloured collision or grounding text on this window together with the audible alarm in dangerous situations. Figure 3.14 shows empirically determined colours and limits of risk levels.

Risk Degree	Risk Level
[0] - [0.35)	LOW RISK
[0.35] - [0.75)	MEDIUM RISK
[0.75] - [1.00]	HIGH RISK

Figure 3.14 : Colours and limits of determined risk levels.

With the left mouse click on the user function included in the visualization module, the target ships can be selected. All AIS information such as distance, bearing, SOG, STW, COG, CPA, TCPA of the selected ships can be observed in real time in the AIS information window that located on the left side of the screen. In addition, according to the user choice, grounding and collision risk results and audible alarms can be displayed separately. Figure 3.15 shows created user interface as a result of whole visualisation process with coloured targets and shallowness, risk monitoring and AIS information windows.

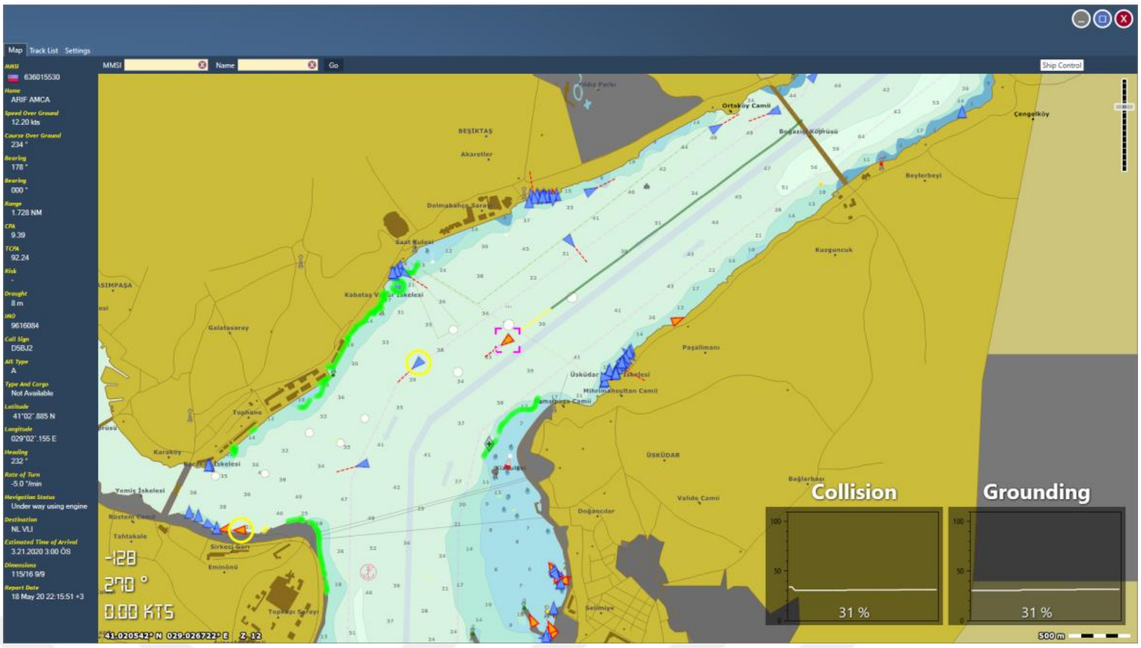

Figure 3.15 : Coloured targets, shallowness and risk monitoring window.

4. FUZZY INFERENCE SYSTEM

Fuzzy logic is a theory that was firstly introduced by Lotfi Zadeh in 1965 (Zadeh, 1965). It is a scientific method that aims to make the machine think like a human being by transferring the experiences and knowledge in the human mind to the computer as a set of rules that is utilised for solving many industrial problems. Application of fuzzy logic method can be found in artificial intelligence, computer science, control engineering, decision theory, expert systems, management science, operations research, pattern recognition and robotics.

In engineering systems, there exist two main sources of information in general that are processed. These are "sensors" that generate variables as numerical data and "experts" that provide linguistic information about the system. Data from sensors is "numerical information", while data from experts is "linguistic" data. In this context, numerical data are represented by numbers, and linguistic information, for example, to express velocity; slow, fast etc. it is expressed in the form of words.

In traditional logical system, decision making takes place within a framework of certainty. So a decision can only be an element of a particular set with crisp statements such as 0-1, Good-Bad, Black-white, which is contrary to the real life. For example, a ship manoeuvre with the classical logic approach is ultimately either risky or risk-free. However, in fuzzy logic, it has a degree of membership that is expressed linguistically (with linguistic variables), such as low risky, medium risky and very risky. In this way, a proposition can become a member of more than one set of decisions with a certain degree of membership.

4.1 Fuzzy Sets and Membership Functions

In classical Boolean sets called crisp sets, there is only a case of whether a value belongs to an existing set or not. However, this consideration is not an appropriate approach to real life. Let the universal set of all speed data that a ship can have is defined as S and consist of subsets as fast (S_f), slow (S_l), or medium speed (S_m).

According to crisp set consideration, a ship navigating at a speed of 10 knots would be a member of only one of these subsets. However, the lower and upper numerical limits of the definition of slow, fast and medium speed cannot be determined precisely and are a logic contrary to the flow of real life. With fuzzy logic approach, 10 knots speed can be element of diverse subsets with certain degrees of membership. For example, it can be an element of fast speed subset by 0.4 degree while it can be an element of medium speed subset by 0.6 degree as well. Figure 4.1 and Figure 4.2 show graphical demonstration of crisp and fuzzy sets specific to the abovementioned ship's speed example.

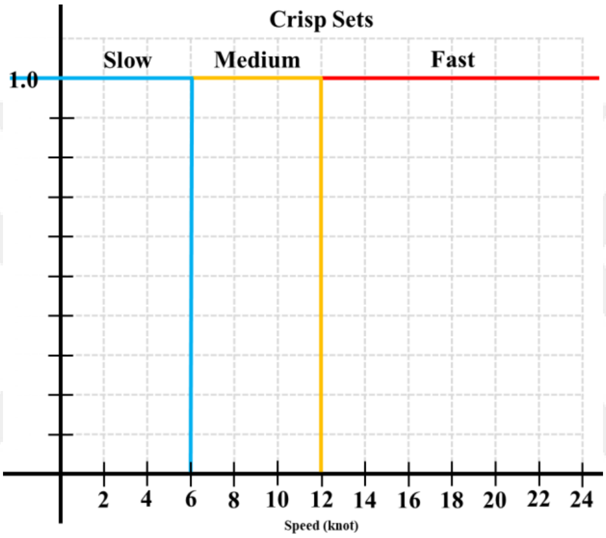

Figure 4.1 : Crisp sets.

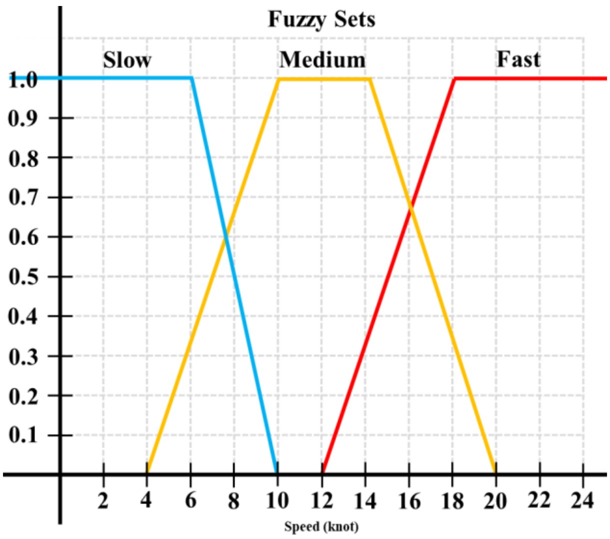

Figure 4.2 : Fuzzy sets.

Consider a universe of discourse X , in which the elements are stand for x. Fuzzy set A in X is defined as follows;

$$A = \{(x, \mu_A(x)) | x \in X\} \tag{4.1}$$

Where $\mu_A(x)$ is membership function of x in A indicating the membership degree of x in A. $\mu_A(x)$ expresses that each element is continuous unit between $[0,1]$.

Membership function is a curve that can be in many types which enable to represent the fuzzy sets graphically (Zhao & Bose, 2002). In other words, membership functions allow to map membership degree between 0 and 1 for each corresponding input value. Mostly employed membership functions are Triangular, Trapezoidal, Gaussian and Sigmoidal. Figure 4.3 shows commonly used membership functions in the literature.

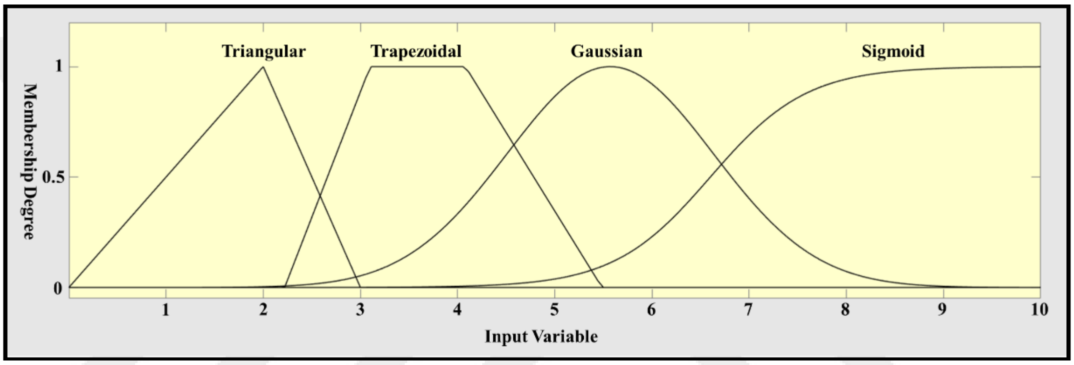

Figure 4.3 : Commonly used membership functions.

4.1.1 Triangular membership function

Three parameters are required to specify a triangular membership function as a, m and b that figure x coordinates of the three vertexes. a is lower limit, b is upper limit and m is a value where $a < m < b$. Figure 4.4 shows a generic shape and vertexes of a triangular membership function.

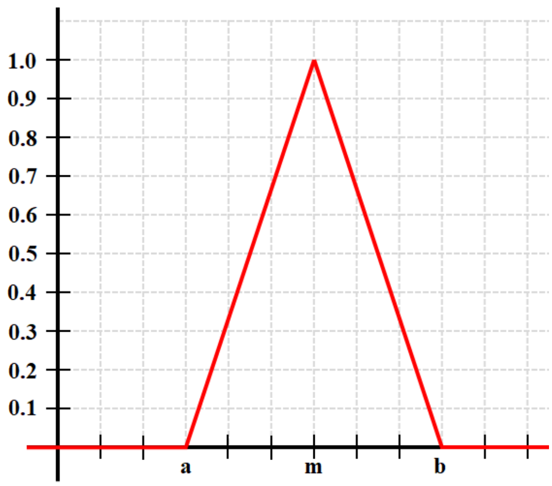

Figure 4.4 : Triangular membership function.

A triangular membership function is defined as follows;

$$\mu_A(x) = \begin{cases} 0, & x \le a \\ \dfrac{x-a}{m-a}, & a < x \le m \\ \dfrac{b-x}{b-m}, & m < x < b \\ 0, & x \ge b \end{cases} \tag{4.2}$$

4.1.2 Trapezoidal membership function

Four parameters are required to specify a trapezoidal membership function as a, b, c and d which correspond lower, lower support, upper support and upper limit respectively. Where $a < b < c < d$. Figure 4.5 shows a generic shape and vertexes of a trapezoidal membership function.

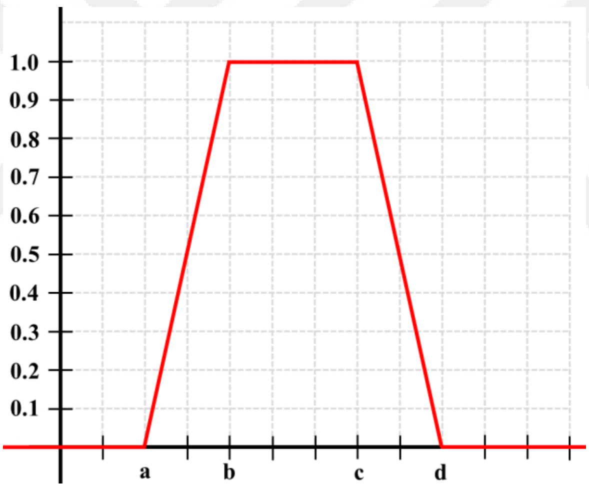

Figure 4.5 : Trapezoidal membership function.

A triangular membership function is defined as follows;

$$\mu_A(x) = \begin{cases} 0, & (x < a) \ or \ (x > d) \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \end{cases} \tag{4.3}$$

There exist two exceptional cases for trapezoidal membership function which are known R and L functions. R-functions correspond to a semi-trapezoidal shape in which some part of the shape is missing and only the right part can be defined, while L-functions are the opposite of this situation. Figure 4.6 and Figure 4.7 shows R and L functions respectively.

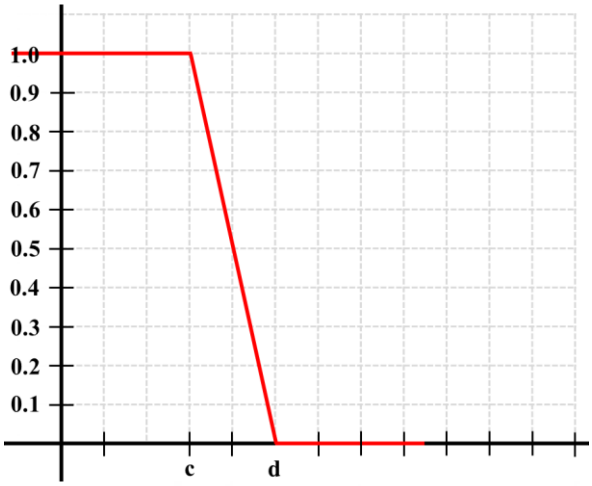

Figure 4.6 : R-function.

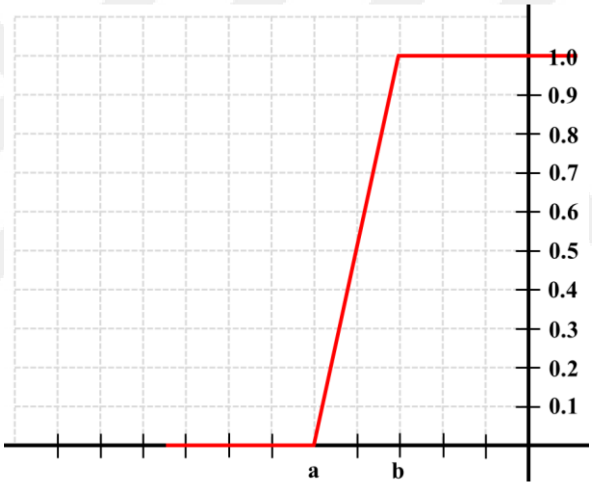

Figure 4.7 : L-function.

4.1.3 Gaussian membership function

Another one of the most preferred membership function is Gaussian membership function to represent linguistic terms, shown in Figure 4.8. It is defined with a standard deviation $k > 0$ and a central value m. The greater k is the wider the bell is. A Gaussian membership function is defined as follows;

$$\mu_A(x) = e^{-\frac{(x-m)^2}{2k^2}} \tag{4.4}$$

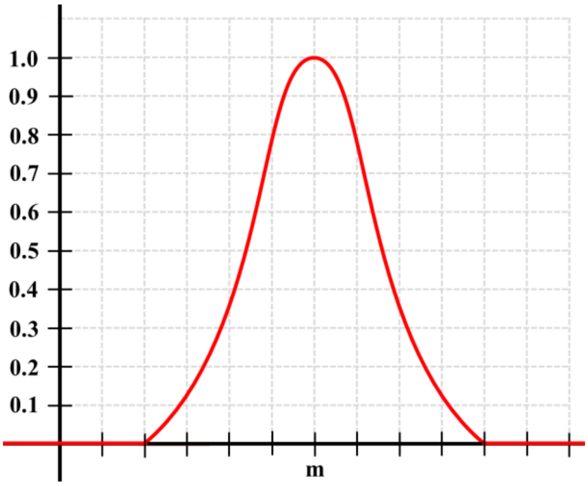

Figure 4.8 : Gaussian membership function.

4.1.4 Sigmoidal membership function

"S" shaped membership function is named as sigmoidal membership function which has two parameters as c and a that correspond distance from the origin and slope of the function respectively. Figure 4.9 shows a sigmoidal membership function. General expression of a sigmoidal membership function is as follows;

$$\mu_A(x) = \frac{1}{1+e^{-a(x-c)}} \tag{4.5}$$

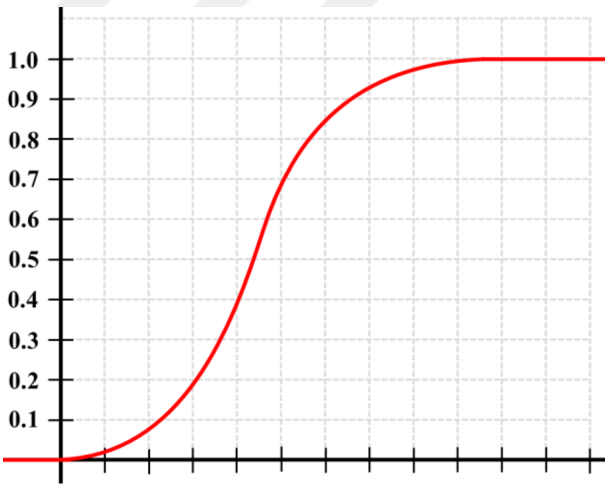

Figure 4.9 : Sigmoidal membership function.

As a natural consequence of its shape, sigmoidal membership function has open right or left form and therefore it is preferred to describe such as "very slow" or "very fast" expressions (Bilgiç & Türkşen, 2000).

4.2 Basic Fuzzy Operators

Fuzzy logic has three basic operators on fuzzy sets as union, intersection and complement. Let μ_A and μ_B are defined membership functions of fuzzy sets A and B. Accordingly, union, intersection and complement operators are defined as follows respectively.

$$\mu_{A\cup B}(x) = Max\left(\mu_A(x), \mu_B(x)\right) \tag{4.6}$$

$$\mu_{A\cap B}(x) = Min\left(\mu_A(x), \mu_B(x)\right) \tag{4.7}$$

$$\mu_{A^c}(x) = 1 - \mu_A(x) \tag{4.8}$$

Figure 4.10 shows union and intersection of two different fuzzy sets of A and B.

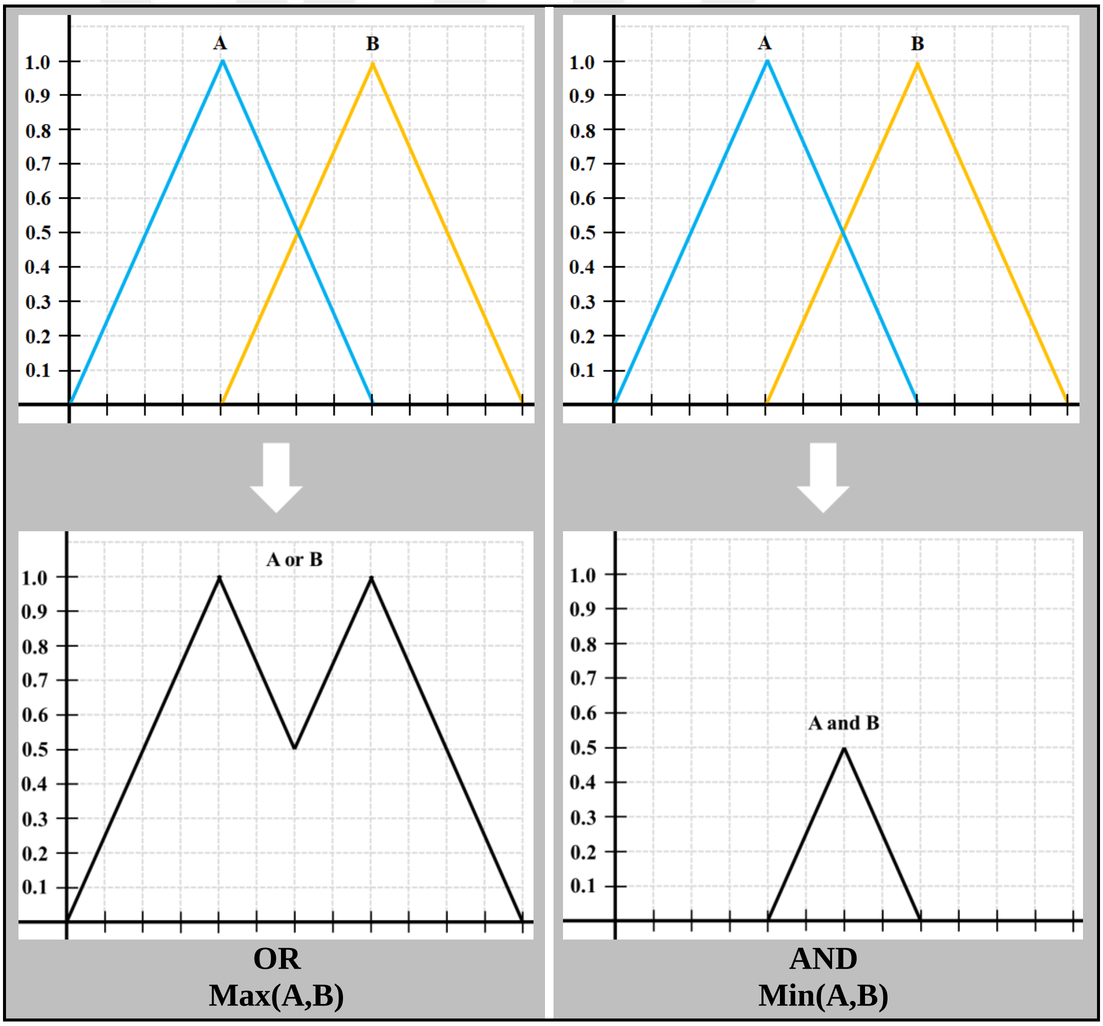

Figure 4.10 : Representation of union and intersection of two fuzzy sets.

4.2.1 Composition of fuzzy sets

The composition of fuzzy sets is obtained by their Cartesian multiplication. The Cartesian product space on fuzzy sets X and Y consists of two types of operations. These are named as fuzzy conjunction and fuzzy disjunction which are knows as T-norm and S-norm operators (Lee, 2004). They are binary operators to generalize intersection and union operations respectively.

Cartesian multiplication expression of fuzzy conjunction is;

$$A \times B = \int_{X \times Y} \mu_A(x)^* \, \mu_B(y) / (x, y) \tag{4.9}$$

Where * stands for T-norm operator and $x \in X$, $y \in Y$, $A \subset X$, $B \subset Y$.

Cartesian multiplication expression of fuzzy disjunction is;

$$A \times B = \int_{X \times Y} \mu_A(x) + \mu_B(y) / (x, y) \tag{4.10}$$

Where $+$ stands for S-norm operator and $x \in X$, $y \in Y$, $A \subset X$, $B \subset Y$.

4.3 Fuzzy Inference Mechanism

Fuzzy Inference System (FIS) is a systematic method of mapping input space to output space by using fuzzy logic which was firstly introduced by Zadeh (1988). FIS deals with converting reasoning process of human's thinking way by using IF-THEN rules. FIS is widely employed method to overcome decision making problems in the literature (Rao & Rao, 2014). It has a wide usage spectrum from engineering, logistics, business, financial to medical industry (Abam & Nsien, 2019; Abdollahi, 2020; Arifin et al., 2020; Ghaghishpour & Koochaki, 2020; Mehrani et al.; Selvam & Sahoo, 2020). A typical FIS structure has four main modules as Fuzzification, Knowledge/Rule Base, Inference and Defuzzification Modules. Figure 4.11 shows basic structure of FIS.

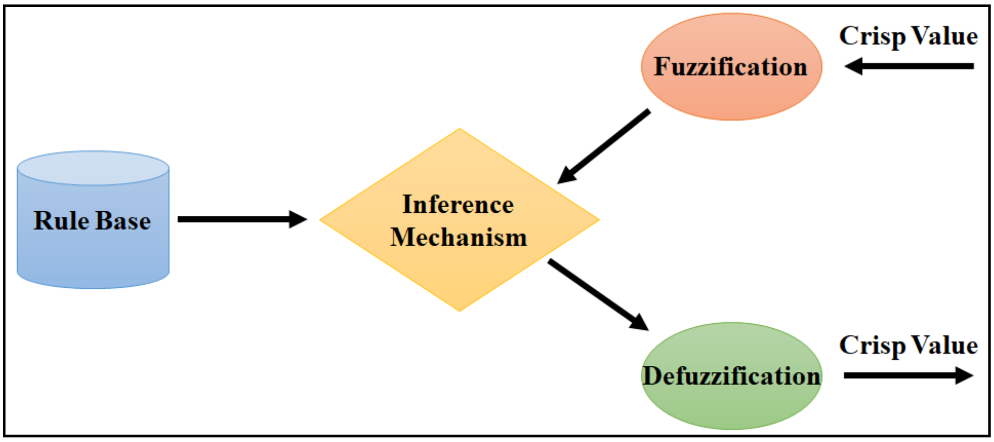

Figure 4.11 : Basic structure of FIS.

In the literature there exist two mostly used different types of fuzzy inference method as; Mamdani Type (1976) and Takagi-Sugeno Type (Rao & Rao, 2014). Although the first two steps (fuzzification and rule base modules) are same, the main difference is having constant or linear output membership function in Takagi-Sugeno Type (Cavallaro & Ciraolo, 2017). It also uses weighted average to calculated crisp output value, while Mamdani employs defuzzification process (Cavallaro, 2015).

In this study, Mamdani Type FIS is employed and for this reason its main modules will be introduced in subsequent sections.

4.3.1 Fuzzification module

Crisp number are transferred to membership grades for linguistic expressions of fuzzy sets by employing fuzzification function (Zadeh, 1965). Membership functions are utilised at this stage to determine the grades of crisp inputs to linguistic terms. In other words, membership grade(s) of a crisp ship's speed value is determined in the Fuzzification Module. Figure 4.12 indicates graphical fuzzification process of crisp input values.

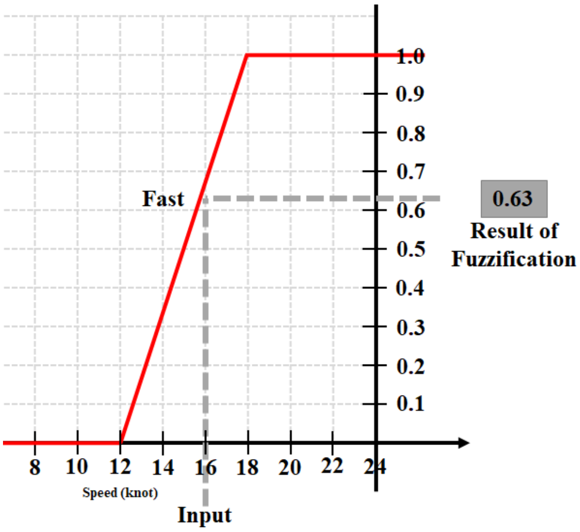

Figure 4.12 : Graphical fuzzification process.

4.3.2 Rule base module

Rule base module stores IF-THEN rules obtained from experts' knowledge. Single fuzzy rule is formed as; $If\ \ x\ is\ A,\ then\ \ y\ is\ B$ where A and B are linguistic variables defined by fuzzy sets. First part of rule ($If\ \ x\ is\ \ A$) is named as antecedent or premise, while second part of the rule ($then\ \ y\ is\ B$) is called implication, conclusion or consequent. Assume $If\ \ "speed"\ is\ \ Low,\ then\ "risk"\ is\ \ Low$ is a sample rule. As can be seen, input value for input variable (Speed) would be always crisp, where output variable of the rule is an entire to fuzzy sets (Low for this rule). This fuzzy set is defuzzified in the abovementioned Defuzzification Module.

Rules can be structured in such a way that single output connected to multi-inputs (MISO – Multi-inputs, Single-output), while it can also be structured in such a way that multi-outputs associated with the multi-inputs (MIMO - Multi-inputs, Multi-outputs). $If\ \ "speed"\ is\ \ Fast\ \ and\ \ "range"\ is\ \ Close,\ then\ "risk"\ is\ \ High$ can be given as an example of MISO rules. In this case, variables of antecedent part linked with fuzzy operators mentioned in Section 4.2 are computed simultaneously and then resolved to a single value between 0 and 1 which is called degree of support for the rule.

4.3.3 Inference Module

Inference Module constitutes core of the FIS mechanism. The rules created with fuzzy operators in the Rule Base Module are operated in Inference Module depending on the crisp inputs that are transferred to fuzzy numbers in the Fuzzification Module. The module comprises of two parts; composition of the antecedents to implication of the rules and aggregation of the consequents. Detailed inference process is given in Figure 4.13.

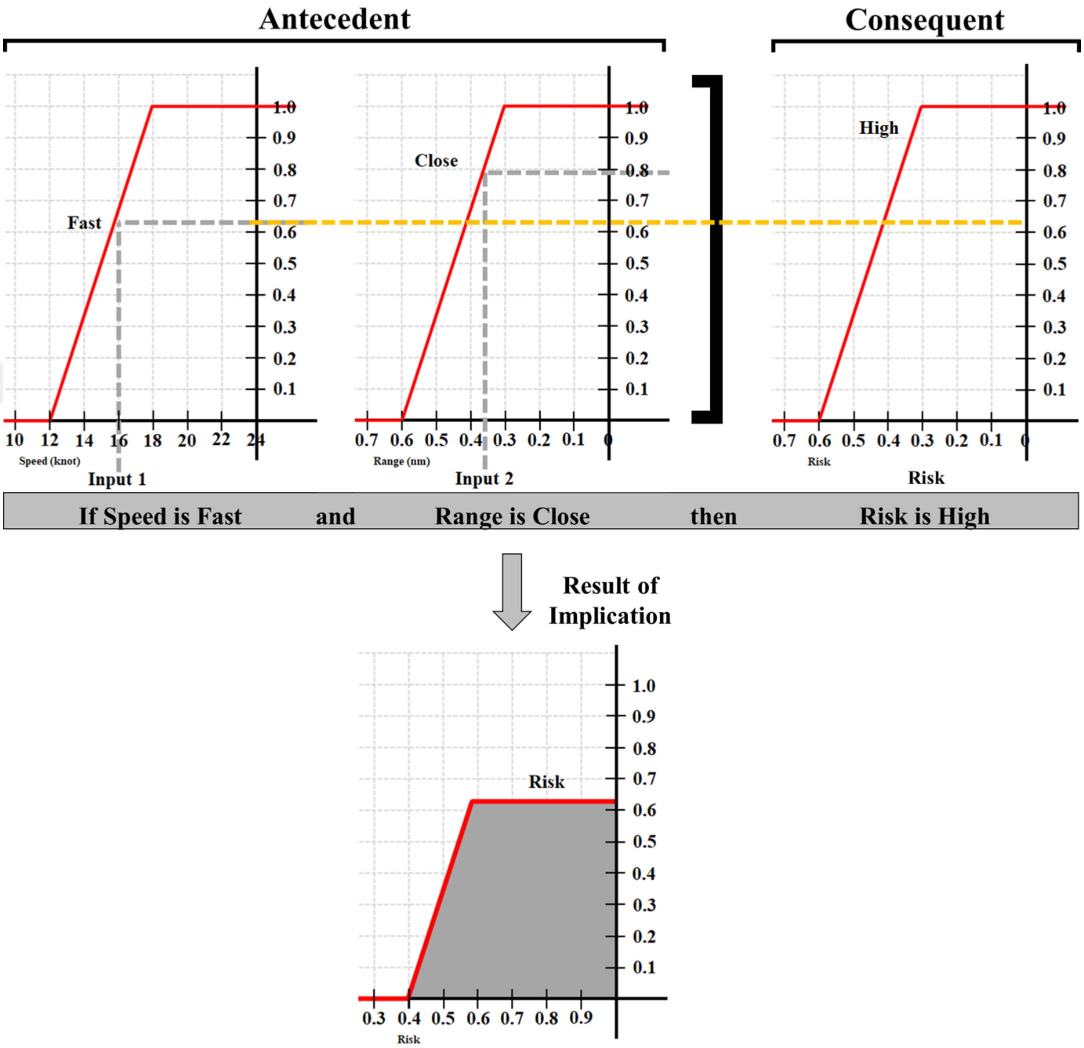

Figure 4.13 : Fuzzy inference process.

In case of more than one of the predetermined rules are working for the inputs that trigger the inference module, the above mentioned processes are applied for each rule separately. After each rule goes through the inference process, the consequent fuzzy sets are obtained as much as the number of rules. In such cases, the obtained consequent fuzzy sets are aggregated and one new fuzzy set is obtained for each output variable. The aggregation methods are named as max (maximum), probor (probabilistic or), and sum (sum of each rules output) (Panigrahi & Mujumdar, 2000).

In the literature, mostly employed aggregation operators are maximum, sum and probabilistic sum operators. In this study maximum aggregation operator is used.

4.3.4 Defuzzification module

The fuzzy data obtained after the fuzzy inference process must be transformed to quantifiable crisp values in order to be used in mathematical calculations and to interpret by a machine. This conversion process is called defuzzification which enables to map a fuzzy set to crisp data. It performs transforming of the aggregated geometric shape that obtained at the end of the Inference module, to crisp value by using some certain methods. Most popular defuzzification methods are centroid, bisector, largest of maximum, smallest of maximum and middle of maximum. In this study, centroid defuzzification method is applied which is the most preferred one (Singh & Lone, 2020). Centroid of a certain fuzzy set is calculated as follows;

$$y = \frac{\int x.\mu_A(x)dx}{\int \mu_A(x)dx} \tag{4.11}$$

where $\mu_A(x)$ is corresponding membership function, x is value of discrete element and n corresponds number of discrete elements in the universe of discourse Figure 4.14 shows centroid of consequent fuzzy set obtained in inference module.

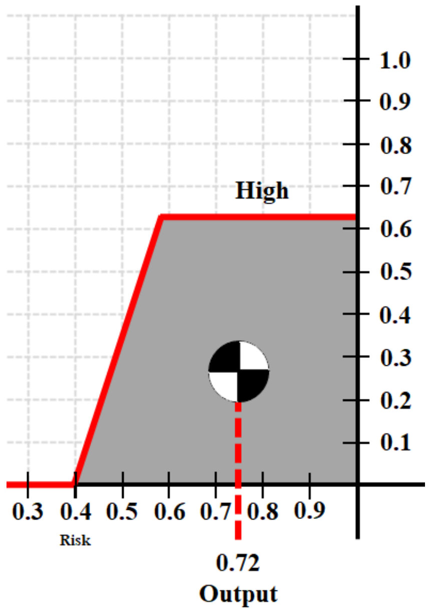

Figure 4.14 : Centroid of consequent fuzzy set.

5. DYNAMIC NAVIGATIONAL RISK ANALYSIS

In this chapter, fuzzy inference system application to determine collision and grounding risks is described. Determining the risk factors, expert elicitation process, regulating the fuzzy sets and their membership functions and establishing risk analysis structure respectively. Description of fuzzy inference system application is given in Figure 5.1.

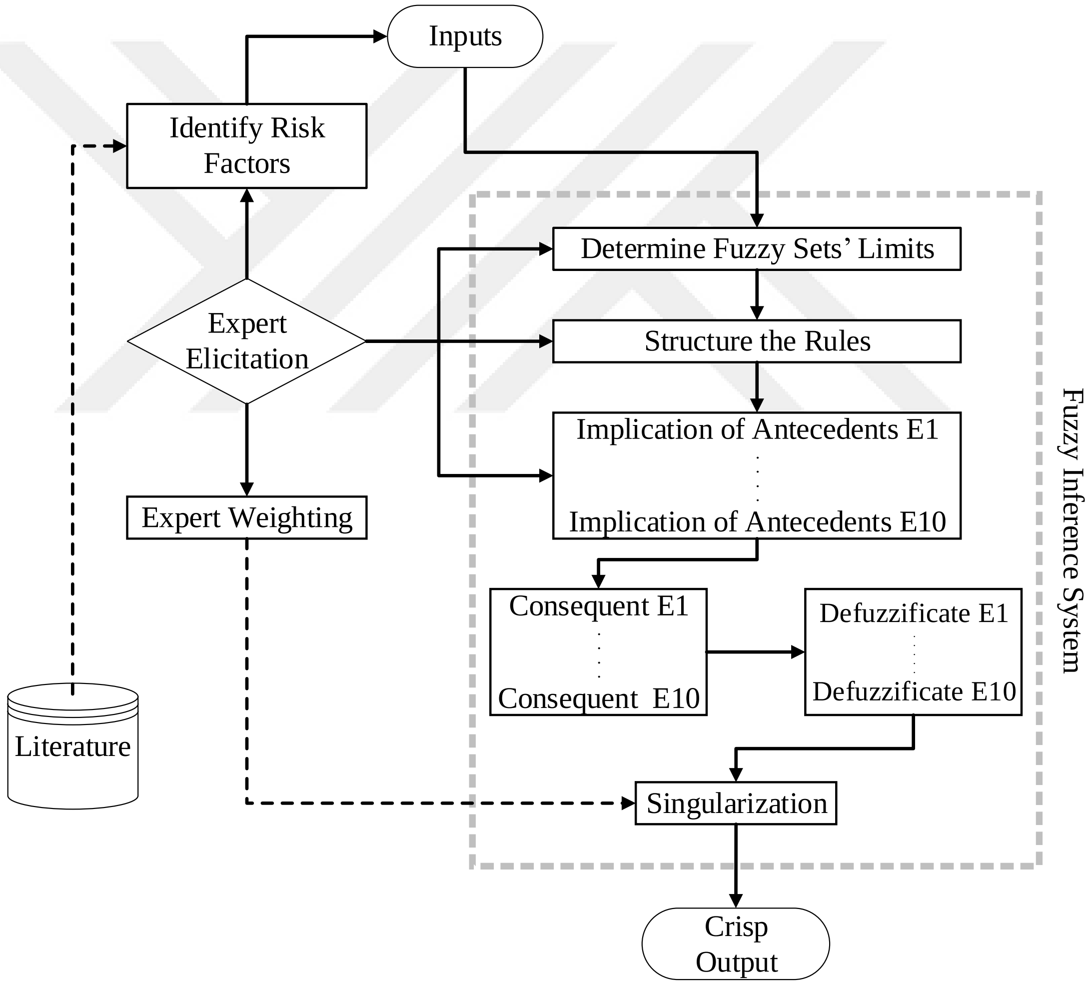

Figure 5.1 : Description of fuzzy inference system application.

5.1 Determining the Risk Factors

In the determination of dynamic navigational risk factors, accident analysis (Akten, 2004; Akyuz, 2015; Hansen & Pedersen, 1997; Samuelides et al., 2009; Uğurlu, Köse, et al., 2015; Uğurlu, Yıldırım, et al., 2015; Yıldırım et al., 2019), maritime risk assessment models (Goerlandt & Montewka, 2015; Kristiansen, 2013; Kujala et al., 2009) and studies on navigational risk factors in the literature were examined in detail and 10 field experts consisting of scholars, marine pilots and shipmasters were also consulted.

The unique and most powerful part of the thesis is that it proposes a system which can perform real-time navigational risk analysis on board and be applied to all waterways due to flexibility of the employed methodology. For this purpose, the obtained dynamic navigational data produced from the navigational equipment as described in Section 3 is processed and included in the calculations. The priority equipment for grounding risk calculations is ECDIS, while the priority equipment for collision risk calculations is AIS. Therefore, the proposed system in the scope of the thesis performs navigational risk analysis within the framework of the maximum data that can be obtained from navigational equipment that can affect the navigational risk.

In the literature analyzed in detail in Chapter 2, it is inferred that DWT of ships, ship type, ship length, ship width, distance to target, speed, relative speed, CPA, TCPA, bearing, relative bearing, COG, heading, angle of collision, BCR, BCT information are used for navigational risk calculations. It is also observed that factors such as traffic density, width of the shoal, rudder angle, track distribution, annual ship movement, position fixing interval, average ships' number, type of waterway, age of ship, flag of ship, pilot request, tugboat request, distance between sequential vessels are also used in navigational risk calculation studies.

All the factors used in the literature are evaluated and the factors that are not appropriate or would not be possible to be included in this study are listed in Table 5.1. Conceptual non-conformity stands for the factors that are not suitable for a real time system that can operate without dependent on a particular waterway. Technical non-conformity means factors that are suitable for a real time system that can operate on board without depending on a particular waterway, but cannot be obtained by means of available navigational equipment.

Table 5.1 : Classification of factors used in the literature.

Included	Conceptual non-conformity	Technical non-conformity
COG	Annual ship movement	Doppler information
CPA	Average ship's number	Rotation direction of screw
Distance	Channel breadth	Rudder Angle
Draft	Day of week	Rudder Type
Length of own ship	Density of local traffic	Pilot request
Length of target ship	Evasion diameter	Ship's age
Relative bearing	Length of path	Tugboat request
Relative speed	Position fixing interval	Wave condition
Ship's breadth	Ship's flag	
Ship’s type	Track distribution	
SOG	Track length	
TCPA	Traffic density	
	Width of the shoal	

The final risk factors obtained by using the factors shown as *“included”* in Table 5.1 directly or indirectly in risk calculations are determined as CPA, TCPA, Relative Bearing, Relative Speed, Ship's Length and Ship’s type which are included to FIS method to determine either grounding or collision risks.

5.2 Expert Elicitation

Expert consultation is executed for determining the subset limits of membership functions of factors. In the same way, expert opinions on the broadest possible spectrum were consulted in the stage of the consequent questioning of the rules obtained by composition of the antecedents. Objective judgment is a very difficult process, as expert evaluations differ according to their own perspective and objective (Lavasani et al., 2015; Senol et al., 2015). In addition, the fact that the expert group is homogeneous or heterogeneous is an important factor affecting the judgement process. According to Ford and Sterman (1998), expert knowledge is biased from his/her own perspectives and aims. Therefore, an expert knowledge impossibly be objective. Expert selection should be managed in a careful manner whether the academic research will be conducted in a heterogeneous expert group or homogeneous expert group. Since heterogeneous expert group include scientists and workers, homogeneous expert group include only scientists. Based on the expert judgments, effect of homogeneous expert group is fewer comparing to the heterogeneous expert group. In a heterogeneous expert group, there are various experts from diverse fields. Due to they will revise all probable opinions, heterogeneous expert group has an advantage. In this study, a heterogeneous expert group is preferred for determining subset limits and composed rule consequences.

At the stage of establishing rules in classical FIS applications, the broadest possible spectrum is taken from experts. At the end of this process, consensus is created and this phase is concluded by determining the rule results that have been made into a single opinion for all rules. This process is named as “singularization”. In this study, a novel approach is presented by including the rule results obtained from each expert to the process based on their degree of expertise without building consensus, contrary to classical method. In other words, the rule evaluations made by each of the 10 members of the expert group consisting of academicians, marine pilots and shipmasters were modelled in the form of 10 different rules sets to affect the final results based on their degree of expertise.

Degree of expertise (weight) is determined based on four parameters as professional position, sea service time, shore service time and education level as given in Table 5.2.

Table 5.2 : Experts’ weighting parameters.

Parameters	Classification	Score
Professional Position	Academician	3
	Marine Pilot	2
	Shipmaster	1
Sea service time (year)	≥16	4
	11 - 15	3
	6 - 10	2
	≤ 5	1
On-Job service time (year)	≥16	4
	11 - 15	3
	6 - 10	2
	≤ 5	1
Level of Education	Doctor of Philosophy (PhD)	3
	Postgraduate Degree	2
	Bachelor’s Degree	1

Table 5.3 shows calculated weights (W) of consulted experts based on abovementioned four parameters.

Table 5.3 : Calculated weights of experts.

No of experts	Professional position	Sea service time (year)	On-Job service time (year)	Level of Education	Weighting factor	w
1	Academician	6-10	11-15	PhD	11	0,13
2	Academician	≤ 5	11-15	PhD	10	0,11
3	Academician	≤ 5	6-10	Postgraduate	8	0,09
4	Marine Pilot	11-15	11-15	Bachelor’s	9	0,10
5	Marine Pilot	6-10	6-10	Bachelor’s	7	0,08
6	Marine Pilot	6-10	11-15	Postgraduate	9	0,10
7	Marine Pilot	≤ 5	6-10	PhD	8	0,09
8	Shipmaster	≥16	6-10	Postgraduate	11	0,13
9	Shipmaster	≥16	≥16	Bachelor’s	10	0,11
10	Shipmaster	6-10	≤ 5	Bachelor’s	5	0,07

5.3 Determination of Fuzzy Set’s Limit

In classical FIS methods, the limits of fuzzy sets are determined by the decision maker and the consultant experts are asked to evaluate the subsets within the specified limits. Ideographically, in this study, fuzzy logic subset boundaries were determined by creating consensus with experts. Thus, it is aimed to represent linguistic variables with closer values to the approximate values in the minds of the experts. The process of determining the limits of linguistic variables is explained separately for grounding and collision risks.

5.4 Fuzzy Sets and Rule Structure for Grounding Risk

As mentioned earlier, the input factors to be included in the calculations for grounding risk analysis are determined as CPA, TCPA, Relative Bearing, Relative Speed, Ship's Length and Ship's Type. The land information considered in the grounding risk analysis is not only the coastline indicated on the chart but also shallowness calculated according to the draft value of the ship. Five of fuzzy sets for factors and risk result are modelled with three linguistic variables representing low, medium and high degrees while linguistic variables of Ship’s Type are modelled with two variables as tanker and others. In a system to be established with linguistic variables in which these inputs are represented, all linguistic variables must be combined with each other at the rule composition stage. Accordingly, $2 X 3^5 = 486$ rules will be obtained which must be associated with the output linguistic variables. The process of obtaining the consequent by evaluating all of the rules will be quite difficult for experts. For this reason, ship type and ship length inputs, which are static data, are evaluated in a separate FIS mechanism, while other inputs are evaluated in a separate FIS mechanism. Two different crisp outputs, called *"static output"* and *"dynamic output"*, will be subjected to a new FIS mechanism and the final grounding risk will be revealed. Figure 5.2 is provided to increase the intelligibility of this unique, multiple FIS application.

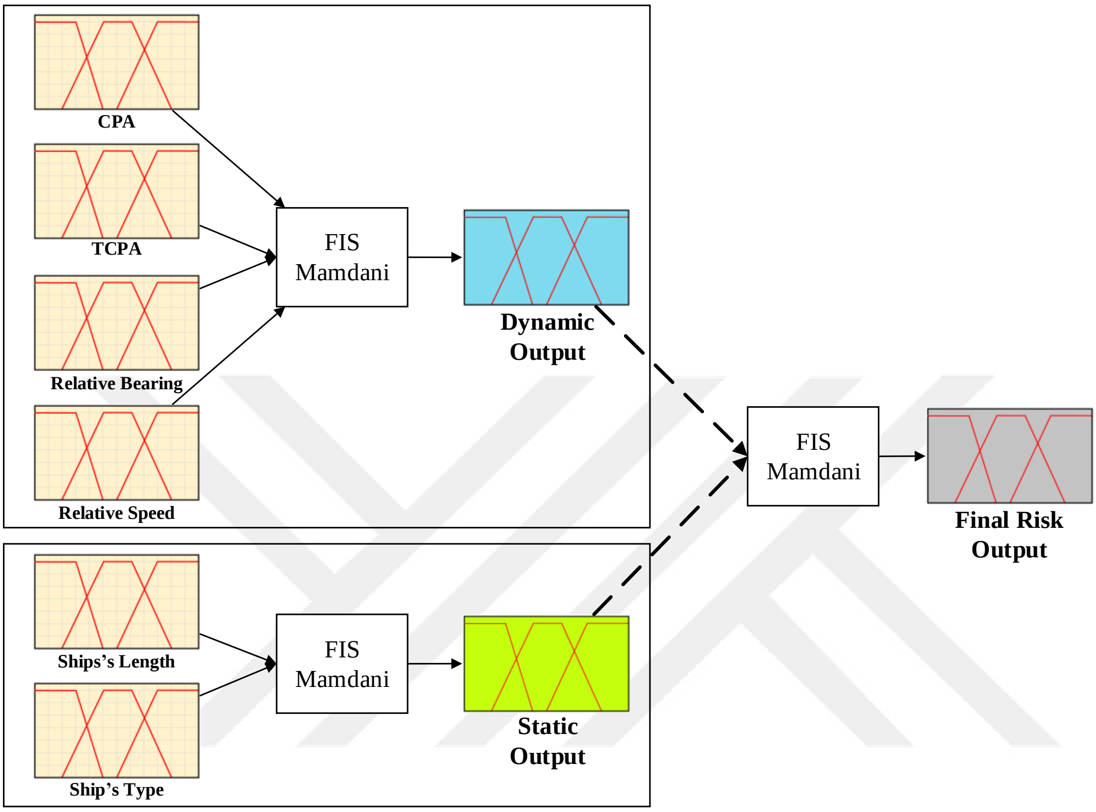

Figure 5.2 : FIS application for grounding risk.

Linguistic terms of variables, their corresponding fuzzy set limits and their number codes for rule representation are given in Table 5.4. Figure 5.3 - Figure 5.7 show membership function and their linguistic terms for each fuzzy set of dynamic input, while membership function and their linguistic terms of static input are shown in Figure 5.8 – Figure 5.10.

Table 5.4 : Linguistic terms and corresponding fuzzy sets for grounding.

Variable	Linguistic Terms	Fuzzy Sets	Number Code for Rule Representation
CPA	Close	(0, 0, 0.4, 1.3)	1
	Medium	(1, 1.3, 1.6, 2)	2
	Far	(1.8, 2.5, 3, 3)	3
TCPA	Insufficient time	(0, 0, 9, 15)	1
	Medium time	(10, 22, 30, 40)	2
	Sufficient time	(30, 50, 60, 60)	3
Relative Bearing	Close to bow	(0, 0, 12, 30)	1
	Close to quarters	(20, 40, 50, 65)	2
	Close to beam	(60, 80, 90, 90)	3
Relative Speed	Fast	(15, 30, 40,40)	1
	Medium	(5, 10, 15, 20)	2
	Slow	(0, 0, 5, 8)	3
Ship's Length	Large	(180, 220, 400, 400)	1
	Medium	(100, 140, 180, 220)	2
	Small	(0, 0, 40, 120)	3
Ship's Type	Tanker	(0, 0, 1, 1)	1
	Others	(1, 1, 2, 2)	2

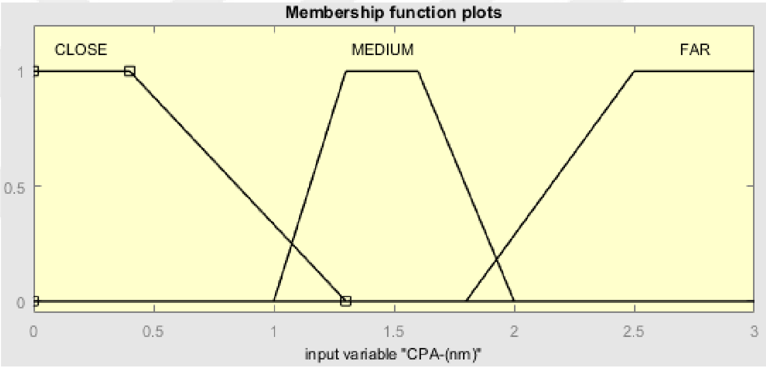

Figure 5.3 : Membership function of CPA input.

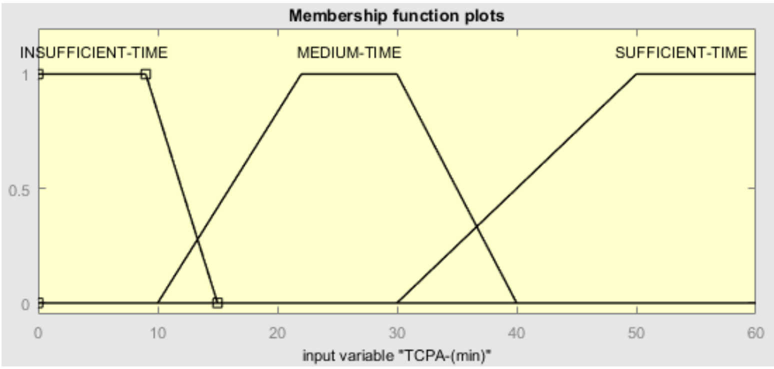

Figure 5.4 : Membership function of TCPA input.

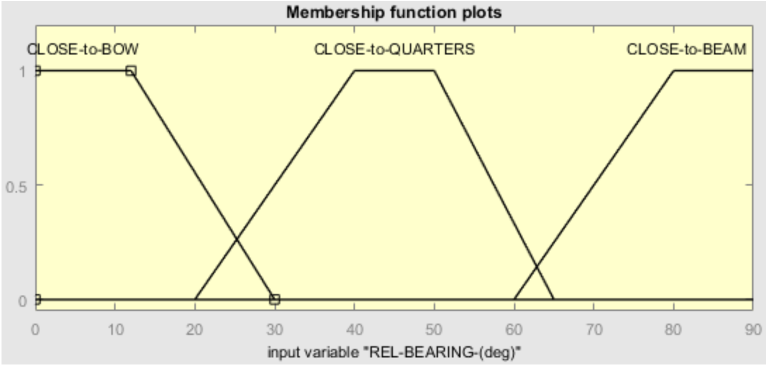

Figure 5.5 : Membership function of Relative Bearing input.

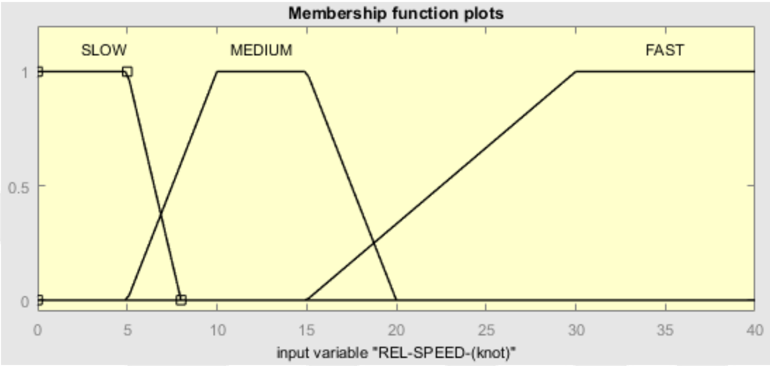

Figure 5.6 : Membership function of Relative Speed input.

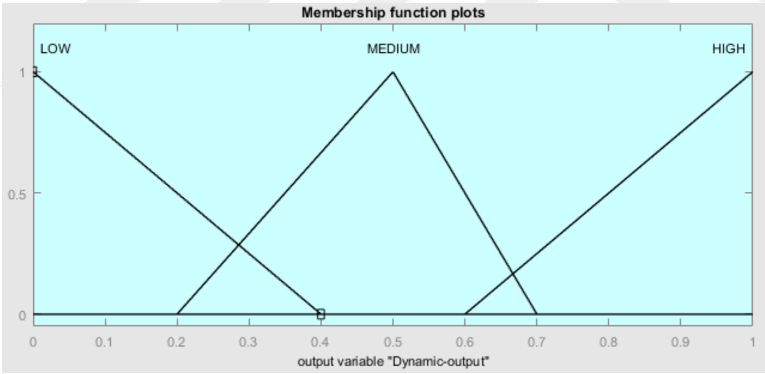

Figure 5.7 : Membership function of dynamic output.

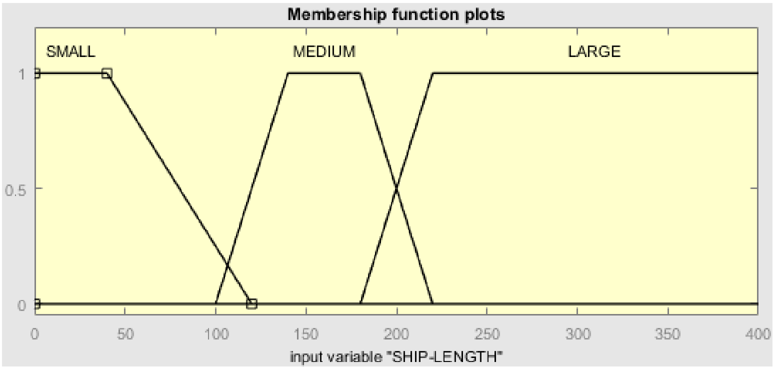

Figure 5.8 : Membership function of Ship’s Length input.

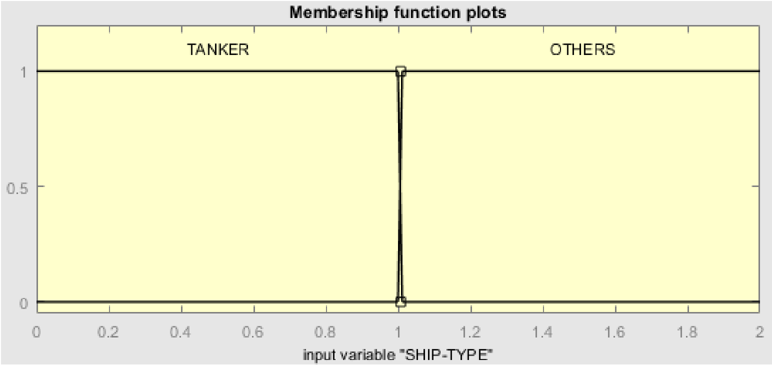

Figure 5.9 : Membership function of Ship's Type input.

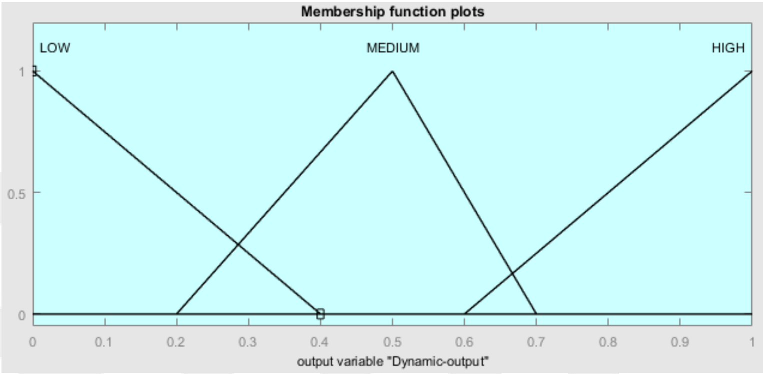

Figure 5.10 : Membership function of static output.

5.4.1 Rule structure for grounding risk

A success FIS application is directly proportional to the rule structure. as a well organised process provides a great advantage for the efficiency and reliability of the system, the rule structure should be prepared professionally. Therefore, separate IF-THEN rules for dynamic and static inputs are created with utmost precision and careful use of expert knowledge. In all of the MISO-structured rules, the composition of linguistic variables is performed with the " *and* " operator. Figure 5.11 shows rules of dynamic inputs, while rules of static input are given in Figure 5.12, which are obtained from judgements of Expert No 1. Number codes of 1, 2 and 3 utilised in the Figure 5.11 and Figure 5.12 represent linguistic terms from dangerous to safer situation membership degrees.

Rule No	CPA	TCPA	Relative Bearing	Relative Speed	Output	Rule No	CPA	TCPA	Relative Bearing	Relative Speed	Output
1	1	1	1	1	1	42	2	2	2	3	2
2	1	1	1	2	1	43	2	2	3	1	2
3	1	1	1	3	1	44	2	2	3	2	2
4	1	1	2	1	1	45	2	2	3	3	2
5	1	1	2	2	1	46	2	3	1	1	2
6	1	1	2	3	1	47	2	3	1	2	3
7	1	1	3	1	1	48	2	3	1	3	3
8	1	1	3	2	1	49	2	3	2	1	2
9	1	1	3	3	1	50	2	3	2	2	3
10	1	2	1	1	1	51	2	3	2	3	3
11	1	2	1	2	2	52	2	3	3	1	2
12	1	2	1	3	2	53	2	3	3	2	3
13	1	2	2	1	1	54	2	3	3	3	3
14	1	2	2	2	2	55	3	1	1	1	2
15	1	2	2	3	2	56	3	1	1	2	3
16	1	2	3	1	1	57	3	1	1	3	3
17	1	2	3	2	2	58	3	1	2	1	3
18	1	2	3	3	2	59	3	1	2	2	3
19	1	3	1	1	2	60	3	1	2	3	3
20	1	3	1	2	2	61	3	1	3	1	3
21	1	3	1	3	3	62	3	1	3	2	3
22	1	3	2	1	2	63	3	1	3	3	3
23	1	3	2	2	2	64	3	2	1	1	3
24	1	3	2	3	3	65	3	2	1	2	3
25	1	3	3	1	2	66	3	2	1	3	3
26	1	3	3	2	3	67	3	2	2	1	3
27	1	3	3	3	3	68	3	2	2	2	3
28	2	1	1	1	1	69	3	2	2	3	3
29	2	1	1	2	2	70	3	2	3	1	3
30	2	1	1	3	2	71	3	2	3	2	3
31	2	1	2	1	1	72	3	2	3	3	3
32	2	1	2	2	2	73	3	3	1	1	3
33	2	1	2	3	2	74	3	3	1	2	3
34	2	1	3	1	1	75	3	3	1	3	3
35	2	1	3	2	2	76	3	3	2	1	3
36	2	1	3	3	2	77	3	3	2	2	3
37	2	2	1	1	2	78	3	3	2	3	3
38	2	2	1	2	2	79	3	3	3	1	3
39	2	2	1	3	2	80	3	3	3	2	3
40	2	2	2	1	2	81	3	3	3	3	3
41	2	2	2	2	2						

Figure 5.11 : Rules of dynamic inputs from Expert No 1 for grounding risk.

Rule No	Ship's Length	Ship's Type	Output
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	2
5	3	1	2
6	3	2	3

Figure 5.12 : Rules of static inputs from Expert No 1 for grounding risk.

Composition of obtained static and dynamic outputs subjected to a new FIS process, which are called *"final inputs"*, are performed as indicated in Figure 5.2. Table 5.5 shows linguistic terms of variables and their corresponding fuzzy set limits where static and dynamic outputs are evaluated as input for final FIS process.

Table 5.5 : Linguistic terms and corresponding fuzzy sets for final grounding FIS.

Variable	Linguistic Terms	Fuzzy Sets	Number Code for Rule Representation
Static Input	Low	(0, 0, 0, 0.4)	3
	Medium	(0.2, 0.5, 0.5, 0.7)	2
	High	(0.6, 1.0, 1.0, 1.0)	1
Dynamic Input	Low	(0, 0, 0, 0.4)	3
	Medium	(0.2, 0.5, 0.5, 0.7)	2
	High	(0.6, 1.0, 1.0, 1.0)	1
Final Output	Low	(0, 0, 0, 0.4)	3
	Medium	(0.2, 0.5, 0.5, 0.7)	2
	High	(0.6, 1.0, 1.0, 1.0)	1

Figure 5.13 shows rules generated end of composition process of static and dynamic inputs that is obtained from judgements of Expert No 1. Number codes of 1, 2 and 3 utilised represent linguistic terms from dangerous to safer membership degrees.

Rule No	Static Input	Dynamic Input	Final Output
1	1	1	1
2	2	1	1
3	3	1	2
4	1	2	1
5	2	2	2
6	3	2	2
7	1	3	2
8	2	3	3
9	3	3	3

Figure 5.13 : Rules of final inputs from Expert No 1 for grounding risk.

All the rules obtained as a result of all expert judgments are subjected to implication of antecedents, consequent and defuzzification processes, as shown in Figure 5.1. In consequent of these processes, 10 crisp outputs, which are the number of total experts, are obtained. Finally, 10 crisp outputs obtained for each rule are multiplied by expert weights and divided by the total number of experts, a single final result output is obtained. The mentioned arithmetic mean process can be expressed mathematically as follows.

$$O = \frac{\sum_{u=1}^{N} w_u E_u}{N} \tag{5.1}$$

Where O is final output for a certain rule. E_u is calculated crisp output of number u expert’s judgment, where $E_u (u = 1, 2, 3 ... N)$.

5.5 Fuzzy Sets and Rule Structure for Collision Risk

As for grounding risk, CPA, TCPA, Relative Bearing, Relative Speed, Ship's Length and Ship's Type factors were used as inputs in calculating risk of collision. Five of fuzzy sets for factors and risk result are modelled with three linguistic variables representing low, medium and high degrees while linguistic variables of Ship’s Type are modelled with two variables as tanker and others. Unlike the grounding risk calculation, targets ships will also be included in the collision risk calculation. In this case, Ship's Length and Ship’s Type inputs will also be included in the calculation for the target ships. Within the scope of this study, model structure of the collision risk is structured taking into account the bilateral ship encounters rather than multi-ship encounter situations. Figure 5.14 shows FIS structure of collision risk calculation process.

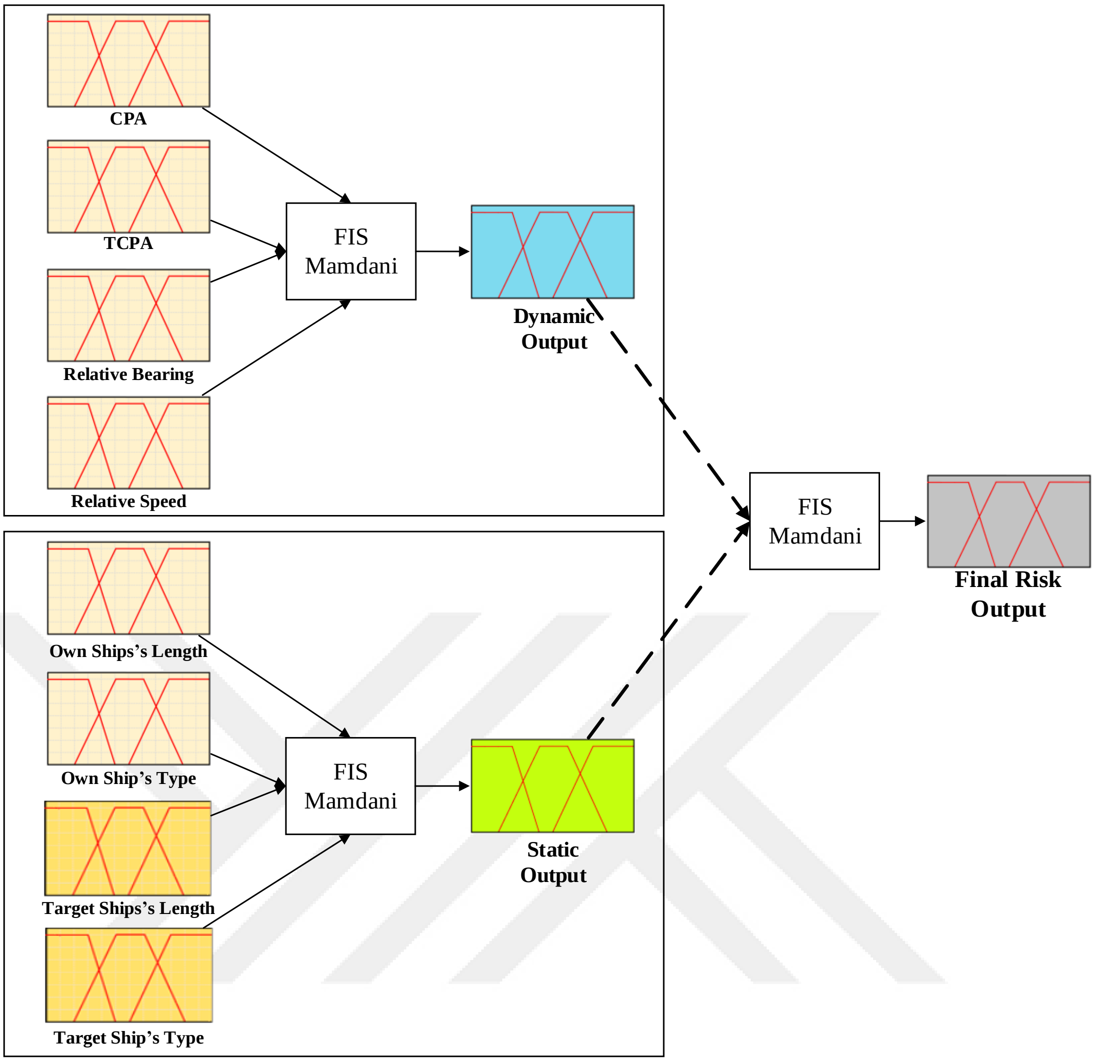

Figure 5.14 : FIS structure of collision risk calculation process.

Linguistic terms of variables and their corresponding fuzzy set limits are given in Table 5.6. Figure 5.15 - Figure 5.19 show membership function and their linguistic terms for each fuzzy set of dynamic input and output, while membership function and their linguistic terms of static input and output are given in Figure 5.20 – Figure 5.24.

Table 5.6 : Linguistic terms and corresponding fuzzy sets for collision.

Variable	Linguistic Terms	Fuzzy Sets	Number Code for Rule Representation
CPA	Close	(0, 0, 0.4, 1.3)	1
	Medium	(1, 1.3, 1.6, 2)	2
	Far	(1.8, 2.5, 3, 3)	3
TCPA	Insufficient time	(0, 0, 9, 15)	1
	Medium time	(10, 22, 30, 40)	2
	Sufficient time	(30, 50, 60, 60)	3
Relative Bearing	Close to bow	(0, 0, 12, 30)	1
	Close to quarters	(20, 40, 50, 65)	2
	Close to beam	(60, 80, 90, 90)	3
Relative Speed	Fast	(15, 30, 40,40)	1
	Medium	(5, 10, 15, 20)	2
	Slow	(0, 0, 5, 8)	3
Own Ship's Length	Large	(180, 220, 400, 400)	1
	Medium	(100, 140, 180, 220)	2
	Small	(0, 0, 40, 120)	3
Own Ship's Type	Tanker	(0, 0, 1, 1)	1
	Others	(1, 1, 2, 2)	2
Target Ship's Length	Large	(180, 220, 400, 400)	1
	Medium	(100, 140, 180, 220)	2
	Small	(0, 0, 40, 120)	3
Target Ship's Type	Tanker	(0, 0, 1, 1)	1
	Others	(1, 1, 2, 2)	2

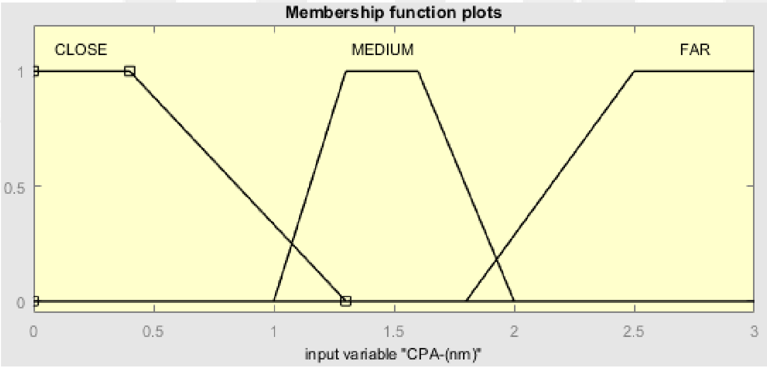

Figure 5.15 : Membership function of CPA input.

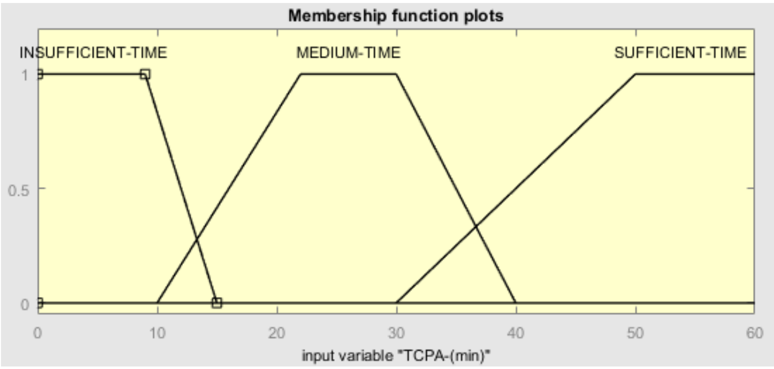

Figure 5.16 : Membership function of TCPA input.

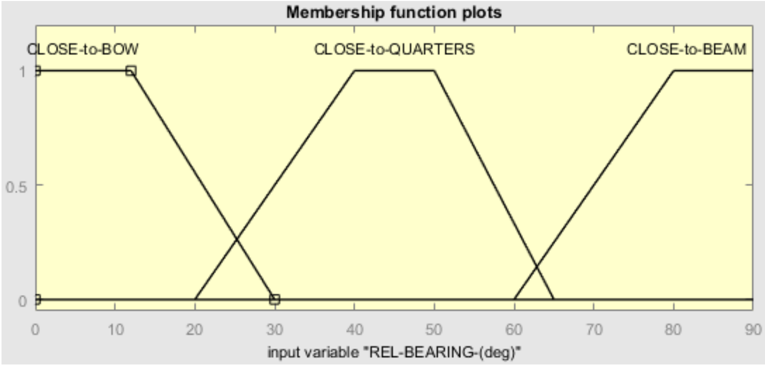

Figure 5.17 : Membership function of Relative Bearing input.

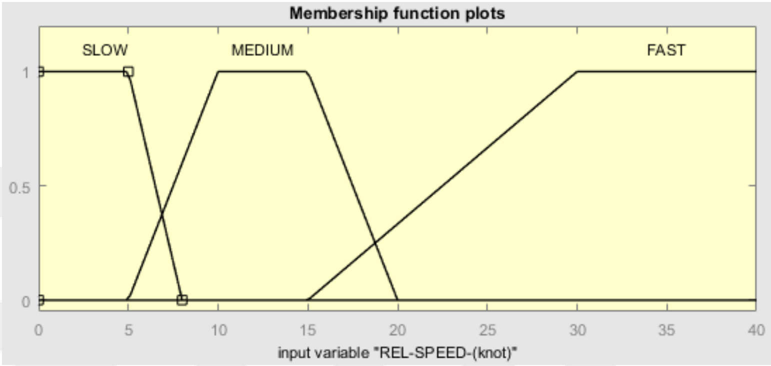

Figure 5.18 : Membership function of Relative Speed input.

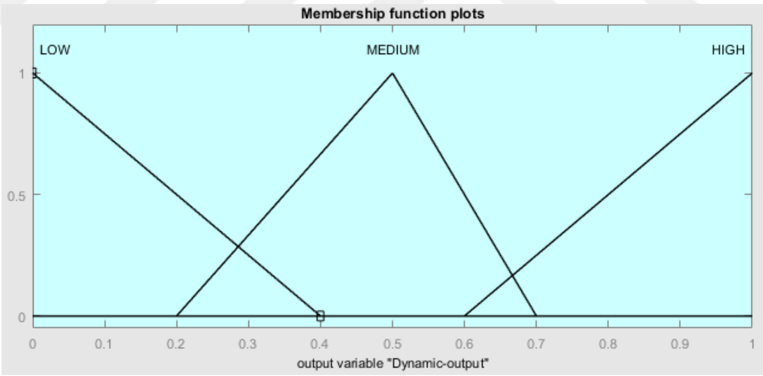

Figure 5.19 : Membership function of dynamic output.

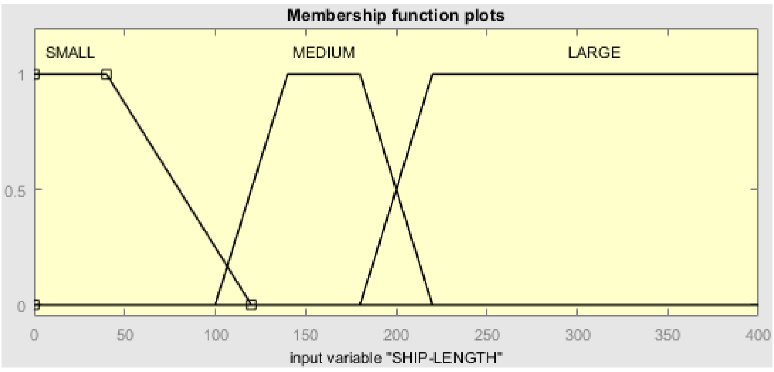

Figure 5.20 : Membership function of Own Ship's Length input.

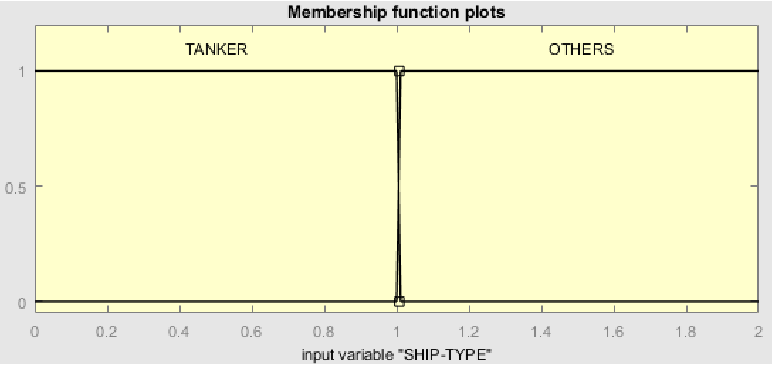

Figure 5.21 : Membership function of Own Ship's Type input.

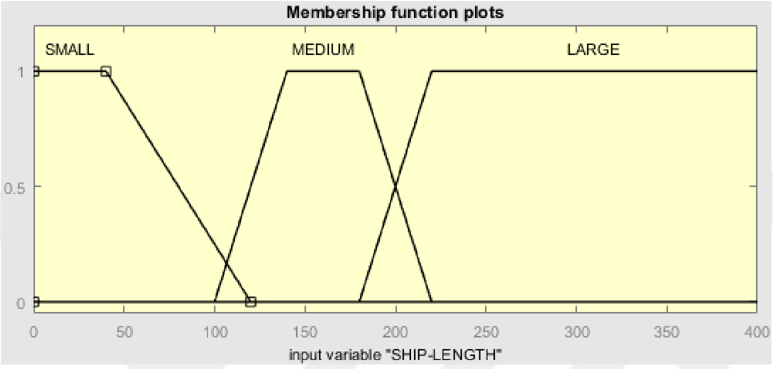

Figure 5.22 : Membership function of Target Ship's Length input.

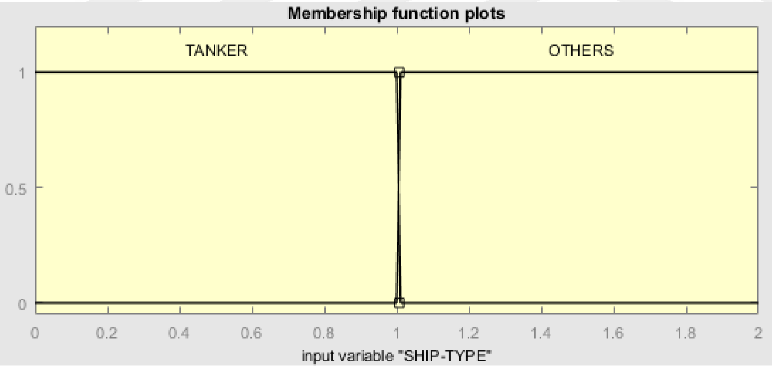

Figure 5.23 : Membership function of Target Ship's Type input.

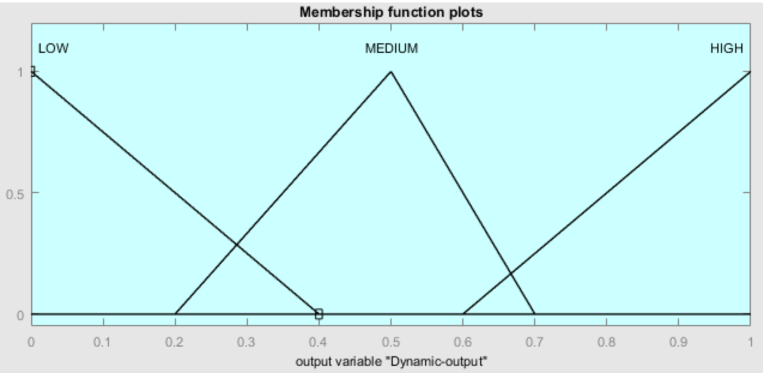

Figure 5.24 : Membership function of static output.

5.5.1 Rule structure for collision risk

As for grounding risk calculation process, MISO-structured rule composition of linguistic variables is performed with the "*and*" operator. Figure 5.25 shows rules of dynamic inputs, while rules of static input are given in Figure 5.26, which are obtained from judgements of Expert No 1. Number codes of 1, 2 and 3 represent linguistic terms from dangerous to safer membership degrees.

Rule No	CPA	TCPA	Relative Bearing	Relative Speed	Output	Rule No	CPA	TCPA	Relative Bearing	Relative Speed	Output
1	1	1	1	1	1	42	2	2	2	3	2
2	1	1	1	2	1	43	2	2	3	1	2
3	1	1	1	3	2	44	2	2	3	2	2
4	1	1	2	1	1	45	2	2	3	3	2
5	1	1	2	2	1	46	2	3	1	1	2
6	1	1	2	3	1	47	2	3	1	2	2
7	1	1	3	1	1	48	2	3	1	3	3
8	1	1	3	2	1	49	2	3	2	1	2
9	1	1	3	3	1	50	2	3	2	2	3
10	1	2	1	1	1	51	2	3	2	3	3
11	1	2	1	2	2	52	2	3	3	1	2
12	1	2	1	3	2	53	2	3	3	2	3
13	1	2	2	1	1	54	2	3	3	3	3
14	1	2	2	2	2	55	3	1	1	1	2
15	1	2	2	3	2	56	3	1	1	2	2
16	1	2	3	1	1	57	3	1	1	3	3
17	1	2	3	2	2	58	3	1	2	1	3
18	1	2	3	3	2	59	3	1	2	2	3
19	1	3	1	1	2	60	3	1	2	3	3
20	1	3	1	2	2	61	3	1	3	1	3
21	1	3	1	3	3	62	3	1	3	2	3
22	1	3	2	1	2	63	3	1	3	3	3
23	1	3	2	2	2	64	3	2	1	1	3
24	1	3	2	3	3	65	3	2	1	2	3
25	1	3	3	1	2	66	3	2	1	3	3
26	1	3	3	2	3	67	3	2	2	1	3
27	1	3	3	3	3	68	3	2	2	2	3
28	2	1	1	1	1	69	3	2	2	3	3
29	2	1	1	2	2	70	3	2	3	1	3
30	2	1	1	3	2	71	3	2	3	2	3
31	2	1	2	1	1	72	3	2	3	3	3
32	2	1	2	2	2	73	3	3	1	1	3
33	2	1	2	3	2	74	3	3	1	2	3
34	2	1	3	1	1	75	3	3	1	3	3
35	2	1	3	2	2	76	3	3	2	1	3
36	2	1	3	3	2	77	3	3	2	2	3
37	2	2	1	1	2	78	3	3	2	3	3
38	2	2	1	2	2	79	3	3	3	1	3
39	2	2	1	3	2	80	3	3	3	2	3
40	2	2	2	1	2	81	3	3	3	3	3
41	2	2	2	2	2						

Figure 5.25 : Rules of dynamic inputs from Expert No 1 for collision risk.

Rule No	Own Ship's Length	Own Ship's Type	Target Ship's Length	Target Ship's Type	Output
1	1	1	1	1	1
2	1	1	1	2	1
3	1	1	2	1	2
4	1	1	2	2	2
5	1	1	3	1	2
6	1	1	3	2	3
7	1	2	1	1	1
8	1	2	1	2	1
9	1	2	2	1	1
10	1	2	2	2	2
11	1	2	3	1	1
12	1	2	3	2	2
13	2	1	1	1	1
14	2	1	1	2	1
15	2	1	2	1	1
16	2	1	2	2	2
17	2	1	3	1	2
18	2	1	3	2	3
19	2	2	1	1	1
20	2	2	1	2	2
21	2	2	2	1	2
22	2	2	2	2	2
23	2	2	3	1	2
24	2	2	3	2	3
25	3	1	1	1	1
26	3	1	1	2	2
27	3	1	2	1	2
28	3	1	2	2	2
29	3	1	3	1	2
30	3	1	3	2	3
31	3	2	1	1	2
32	3	2	1	2	2
33	3	2	2	1	1
34	3	2	2	2	3
35	3	2	3	1	2
36	3	2	3	2	3

Figure 5.26 : Rules of static inputs from Expert No 1 for collision risk.

Composition of obtained static and dynamic outputs subjected to a new FIS process, are performed. Table 5.7 shows linguistic terms of variables and their corresponding fuzzy set limits where static and dynamic outputs are evaluated as input for final FIS process.

Table 5.7 : Linguistic terms and corresponding fuzzy sets for final collision FIS.

Variable	Linguistic Terms	Fuzzy Sets	Number Code for Rule Representation
Static Input	Low	(0, 0, 0, 0.4)	3
	Medium	(0.2, 0.5, 0.5, 0.7)	2
	High	(0.6, 1.0, 1.0, 1.0)	1
Dynamic Input	Low	(0, 0, 0, 0.4)	3
	Medium	(0.2, 0.5, 0.5, 0.7)	2
	High	(0.6, 1.0, 1.0, 1.0)	1
Final Output	Low	(0, 0, 0, 0.4)	3
	Medium	(0.2, 0.5, 0.5, 0.7)	2
	High	(0.6, 1.0, 1.0, 1.0)	1

Figure 5.27 shows rules generated end of composition process of static and dynamic inputs that is obtained from judgements of Expert No 1.

Rule No	Static Input	Dynamic Input	Final Output
1	1	1	1
2	2	1	1
3	3	1	2
4	1	2	1
5	2	2	2
6	3	2	2
7	1	3	2
8	2	3	3
9	3	3	3

Figure 5.27 : Rules of final inputs from Expert No 1 for collision risk.

5.6 Case Study

In this section, the collision and grounding risk analysis of a ship navigating in İstanbul Strait is carried out with the proposed method. Thanks to the integration of real AIS data and ENC charts into the created model, real-time monitoring of all sea traffic in the region is provided. In order to increase the clarity of the case study in which a tanker is entering the İstanbul Strait from the North entrance is preferred, the screenshots obtained from the model reflecting the risk status of the whole passage are presented. The tanker selected as sample has 10 meters of draft, 178 meters of length and 32 meters of width. Figure 5.28 provides screenshots of all navigation process indicating colourised ship track based on her instant risk degree originated from collision and grounding calculations.

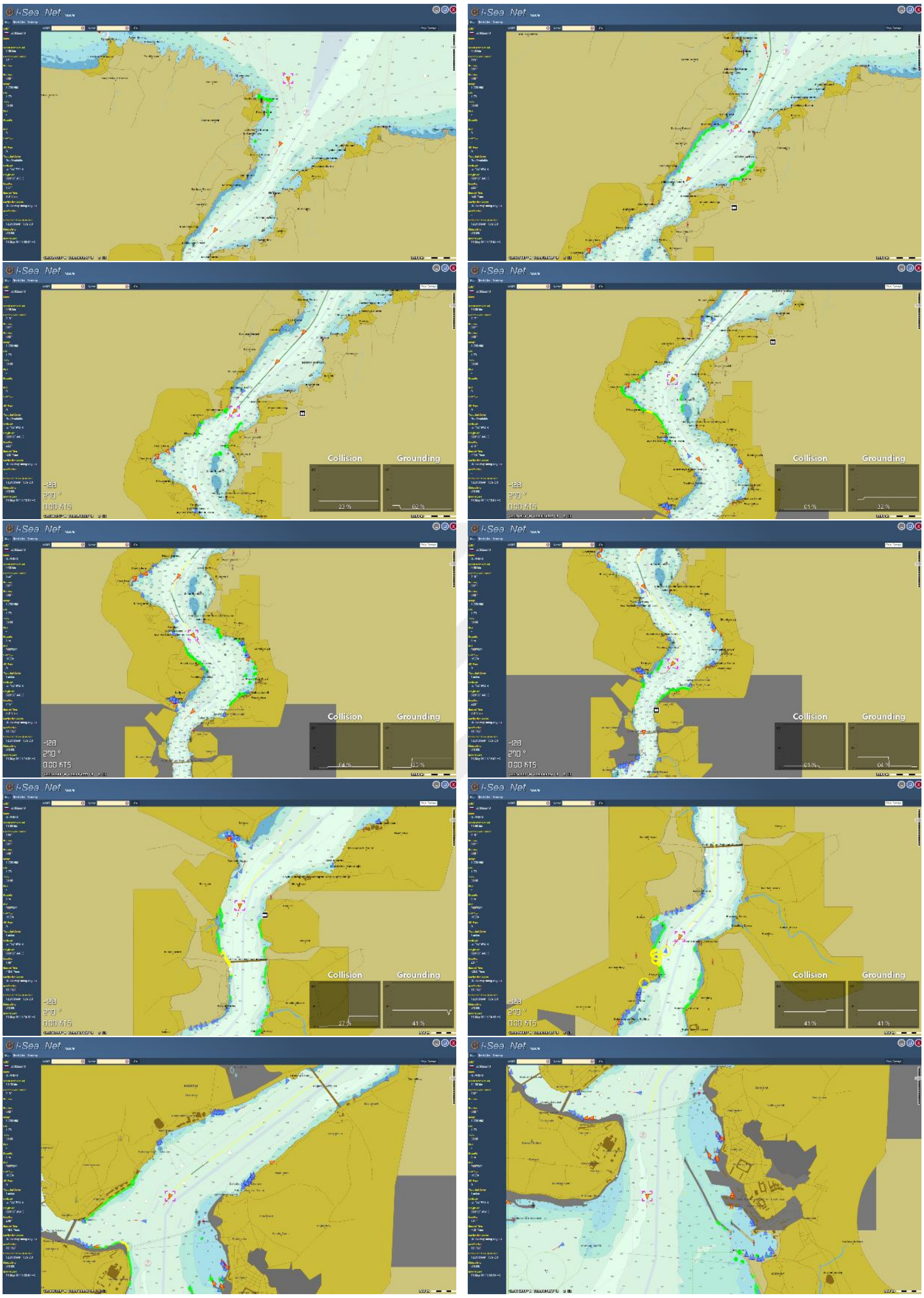

Figure 5.28 : Screenshots of all navigation process.

According to the results of the analysis, the İstanbul Strait navigation, which is completed without encountering any a high-risk situation, was a scenario where mostly low and medium risks are emerged. The tanker, which entered the İstanbul Strait from the North entrance, proceeds approximately 10 knots in the middle of the channel until the abeam of Fil Point with observed low risk level.

Later, low risk level continued until Kavak Point and Mesar Point. The turn of Büyükdere, the first turn encountered by ships entering the North, and also the widest part of the Strait, is begun. During this turn, grounding risk increased up to medium levels due to Umur shallows on the port side and Kireç Point on the bow of the tanker. Outside of the traffic separation scheme after the turn is completed, the upcoming local traffic vessel on the starboard side has caused an increase on the collision risk up to medium levels. After the Yeniköy return, it is observed that the risk increased up to medium levels due to the ships located around Baltalimanı during the Kanlıca Point turn, where one of the strongest surface currents of the Strait is observed, and also because of the European pillar of the Fatih Sultan Mehmet Bridge. The risk level increased to medium levels again due to the local traffic ships observed on the bow during the Kandilli turn, which is another strongest surface current point in the Strait. That moment of the scenario was the situation where the highest risk level was observed throughout the entire passage. The risk level continued at low and medium levels until the turn of the Sarayburnu. During the turn of the Sarayburnu, low risk level is observed and thus the İstanbul Strait passage is completed.

6. CONCLUSIONS

Marine traffic, which has an increasing importance in terms of global freight and passenger transportation, has increased significantly in recent years and has brought some navigational safety problems. An increase was observed especially in collision and grounding accidents in especially dense waterways. In order to find solutions to this problem, many academic studies have been carried out that offer different sights and analysis methods. In Chapter 2, these studies were examined in detail and it is assessed that although the studies in the literature constitute an academic value in terms of their proposed methods and approaches, it has been evaluated that many of them could not be address a fully sufficient solution in terms of applicability, namely the solution of the problem faced by the industry. For this reason, within the scope of this study, a collision and grounding risk analysis algorithm has been developed, which can provide decision support to the officer on watch, work integrated with real navigational equipment and has a strong academic aspect. The algorithm, which consists of four main modules, basically obtains ship data from AIS, shallowness and land information from the ENC and performs navigational risk analysis by using FIS method. The algorithm is modelled with NMEA 0183 data exchange protocol which enables to be integrated with real navigational equipment and work on board in real-time. In this section, the developed new model is examined and its strengths and probable weaknesses are discussed in terms of applicability, innovation and academic aspects.

The fuzzy inference method used in the thesis is classified as one of the artificial intelligence methods employed in many disciplines such as from medicine to branches of engineering science. FIS method enables to evaluate all of the input combinations by the field experts. As a result, a mechanism that determines the risk result corresponding to real-time input values obtained under operational conditions has been created, which is one of the strongest aspects of the thesis. In addition, unlike the classical FIS approach, as explained in Chapter 5, the opinions obtained from the consulted experts were not formed into a single set of decisions by building a consensus.

Instead, each of the expert opinions was subjected to the FIS process individually and crisp outputs were obtained as much as the number of experts for each decision. Then, the crisp outputs of each expert were gathered in proportion to the expert's degrees and a single crisp result was obtained. This practice has been carried out in order to prevent the experts from being affected by each other during the consensus phase, which must be established while creating a single set of rules. In this way, the thesis work has been made more methodologically stronger with a more objective FIS application where the expertise levels are also taken into consideration.

Another strength of the proposed model, which distinguishes it from most of the studies in the literature, is that it offers a solution against the calculation of both collision and grounding risks at the same time.

The studies in the literature analyzed in Chapter 2 and the proposed model are compared in Table 6.1 in terms of the problem, method used and the factors included in the calculations. The letter codes are the same as the codes used in Table 2.1.

Table 6.1 : Comparison of literature with the proposed model.

Letter Code	Problem	Method	Factors
Proposed Study	Collision and Grounding risk	Fuzzy Inference System	COG of OS, COG of TS(s), CPA, TCPA, distance of target(s), Draft, Heading of OS, Heading of TS, length of OS, length of TS, relative bearing of target(s), relative speed of target(s), ships' breadth, ships' type, SOG, GPS location onboard
M1	Collision and Grounding risk	Analytical	Traffic density, width of the shoal, speed, evasion diameter, relative speed, passing ships' speed.
M2	Collision and Grounding risk	Analytical formulation of molecular collision theory	Traffic density, track length, channel breadth, length of path, distance between vessels, length of ship.
M3	Collision avoidance	Analytic geometry solution	Speed, rudder angle and evasive manoeuvre reaction time
M4	Collision risk	Analytical formulation with subjective judgement value	Relative bearing, relative distance between ships, length of OS, speeds of ships
M5	Collision and Grounding risk	Analytical and probabilistic (FTA)	DWT, length, type of ship, width of area, track distribution, annual ship movement, distance to bend, position fixing interval
M6	Grounding risk	Probabilistic with FTA	NIL
M7	Collision and Grounding risk	Analytical and probabilistic (FTA)	DWT, length, type of ship, width of area, track distribution, annual ship movement, distance to bend, position fixing interval
M8	Collision avoidance	Artificial intelligence with fuzzy inference	CPA, ship's length, TCPA
M9	Collision risk	Analytical formulation with probabilistically obtained consequence	Average ship's number, speeds of ships, angle between OS and TS
M10	Collision avoidance	Artificial intelligence with fuzzy neural inference	Speed of ships, range, CPA, type of waterway and time of day
M11	Collision and Grounding risk	Analytical and probabilistic (BBN)	DWT, length, type of ship, width of area, track distribution, annual ship movement, distance to bend, position fixing interval
M12	Collision risk	Artificial intelligence with fuzzy inference	ships' length, speed and sea state
M13	Collision and Grounding risk	Analytical and probabilistic (FTA)	DWT, length, type of ship, width of area, COG distribution, annual ship movement, distance to bend, position fixing interval
M14	Collision risk	Probabilistic with paired-comparison	Ships' type, length, age, flag, pilot request and tugboat request were included to vessel attributes and distance between sequential vessels, current, geographical difficulties of related slice and density of local traffic
M15	Collision risk	Analytic geometry solution	Manoeuvrability of ships, angle of intersection and relative bearing of vessels
M16	Collision avoidance	Analytical	Length of ships and intersection angle of headings
M17	Abnormal navigation detection	Artificial intelligence with fuzzy inference	speed and course variation of ships
M18	Collision risk	Artificial intelligence with D-S evidence theory	CPA, TCPA and distance to TS
M19	Sinking risk after a collision	Probabilistic with BBN	Ships' types, ships' sizes, collision angles, collision speed and the time of day of a probable collision
M20	Collision risk	Artificial intelligence with fuzzy inference	CPA, TCPA, distance, bearing
M21	Collision risk	Artificial intelligence with neural network	initial position and COG vectors
M22	Collision risk with near miss	Analytical	CPA and TCPA
M23	Collision risk with near miss	Analytical	Distance of encountered ship, relative speed and variance of ships' heading
M24	Collision risk	Artificial intelligence with fuzzy inference	CPA, TCPA, bearing, BCR and BCT of TS, visibility, time of day and wave condition
M25	Collision risk	Analytical formulation with subjective judgement and safety index	Type and length of ship, relative speed, distance, encounter situations, time of day, day of week
M26	Collision and Grounding risk	Probabilistic with fuzzy FTA	Closeness to shallowness, ii) Resetting period of BNWAS, Deviation from intended course, CPA, rate of plotted vessels, meteorological conditions
M27	Collision risk	Artificial intelligence with fuzzy inference	CPA and TCPA
M28	Collision risk	Analytical formulation of molecular collision theory	SOG, COG, ships' positions, LOA and breadth

It is clear that many studies do not address both the risks of collision and grounding at the same time. Studies where only collision or grounding risk analysis are presented may not fully meet the expectations of the maritime transportation industry. In addition, these studies are not modelled to work integrated with real navigational equipment. Some of them are operated with data obtained from simulators, while some are conducted with experimentally created virtual data. However, the collision and grounding risk calculation structures created in this study provide solutions for both problems individually with the FIS method. In addition, the algorithm modelled with the NMEA 0183 protocol infrastructure has been enabled to work directly by integrating with AIS, so that the collision risk calculation can be performed in real time onboard. As a result of reading S-57 charts and obtaining necessary data, it is provided to calculate the risk of grounding onboard in real time as well.

As can be seen in Table 6.1, it is aimed to include all possible factors that may affect the risks of collision and grounding. All technically available factors that may affect the dynamic navigational risks are included in the calculations, directly or indirectly. COG of own ship, COG of target ship (s), CPA, TCPA, distance of target (s), draft, heading of own ship, heading of target ship, length of own ship, length of target ship, relative bearing of target (s), relative speed of target (s), ships 'breadth, ships' type, SOG, GPS location onboard data are factors included in the algorithm.

Another strength of the proposed model is that ships are not considered as a single-point. When the literature is examined, including ship domain studies, the ships are considered as single-point object. Even if an algorithm created with such an approach is capable of working on board with integration of navigational equipment, it will consider all the ships as if they consisted of single-point on a position obtained from GPS receiver and perform the risk calculations accordingly. There might be a risk of deterioration to accurately reflect the risk consequences of models prepared by neglecting the ship's width and length, especially when the large ships are close to the danger situation. This study proposes a novel solution to this problem is that the shape of the ship is formed in its real size with the information obtained from AIS. Ship forms created in real dimensions are perceived as a set of multi-points consisting of points in which a distance of less than 10 meters between each one, and risk calculations of collision is carried out in real time by including all of these points into calculations.

Similarly, the default shallow contour information obtained as a result of the S-57 reading process are converted to the required real shallow contours based on ship's instant draft which is evaluated as a set of multi-point with a distance of 10 meters between them and included in the collision risk calculations.

The model, which is able to run in real time during the navigation, supports the decision making process by increasing the situational awareness of the watch officer. For this purpose, interface indicates real-time maximum risk value and colourizes all targets according to their risk degrees. Also it provides an alarm support system in case of high-risk level conditions, which includes flashing visual indicator of the dangerous targets with an audible warning. On the other hand, in addition to operational use, it is assessed that the model can also be used to measure the long-term safe navigational performances of watch officers by the utilising its capability of continuous recording of risk graphs and thus is able to provide support for critical issues such as determining possible training needs. Modifying and development the proposed algorithm to systematically determine the training needs is one of the main topics that are aimed to be addressed within the scope of further studies.

The VTS system which is usually established for the observation of dense waterways is built on a human oriented operations. Operators are in charge of management the traffic by continuously observing the vessels and if needed, giving information, advice, warning or instruction within their sectors/areas of responsibility. Occasionally, it may not be possible for operators to show maximum attention to all targets in their areas of responsibility at the same time. From this point of view, it is considered that it may be beneficial to use the model for the management of dense sea traffic by VTS operators due to its acquired ability on providing decision support by increasing situational awareness. In addition, in light of the statistical information to be obtained as a result of the long-term use of the algorithm in VTS areas, it is considered that it will contribute to the constitute safety recommendations such as maximum safe speed, minimum distance between ships, safe routes, or take safety measures.

Navigational safety has also an important role in the autonomous ship concept, which is one of the most prominent research topics in today's maritime research. It is considered that this model presented within the thesis will constitute a starting point for autonomous ship technology navigational safety. Because, in order to establish a safe autonomous navigation of a ship, two important skills must be acquired to autonomous algorithm. One of these abilities is the perception of navigational hazards and the other is the correct decision application against perceived navigational hazards. From this point of view, it is considered that the proposed model will be the basic study for autonomous ship algorithms in determining the navigational risks and thus navigational hazards.

Although the proposed model can respond to the need to provide decision support by performing both collision and grounding risk assessment on board ship in real-time, the algorithm has some limits. For example; despite some factors are included in the risk assessment in some studies in the literature, they are not included in the calculations in the proposed model due to technical limitations or their unsuitability for the real-time navigational risk assessment concept. Conceptual limiting factors; annual ship movement, average ship's number, channel breadth, day of week, traffic density, density of local traffic, length of path, ship's flag, track distribution, track length and width of the shoal which are non-real time statistical data used in some studies in the literature. They can be used for capacity estimation purpose of specific regions and thus were not included in the model as they are conceptually inappropriate for a real time algorithm. Although there are factors that can strengthen the dynamic navigational risk analysis algorithm such as rudder angle and Doppler information cannot be produced and used by navigational equipment on all ships. Due to technical limits, it was not included in the algorithm which focuses on the ability to work on all ships. Factors such as rotation direction of screw, rudder type, ship's age are other technical limiting factors that are desired to be used in the algorithm but cannot be included in the calculations due to the lack of data that an autonomous algorithm can obtain.

As a result, despite the weaknesses of the model, it is considered that its methodical and technical strengths and novelty are considerably prominent. It is believed to contribute to the concept of autonomous ship as a strong basis in terms of hazards awareness of autonomous algorithm. The model, which will provide decision support by real-time risk analysis on the ship, will be enhanced with subsequent studies and will provide the potential training needs of the watch officers as an output in an autonomous way. The model, which can also be used to contribute to the situational awareness of VTS operators, will be developed in a way that will autonomously create safety recommendations such as maximum safe speed, minimum distance between ships, safe routes.

REFERENCES

Abam, A. O., & Nsien, E. F. (2019). Cost Escalation Management In Tertiary Institutions Using Partial Least Squares and Fuzzy Inference System. *International Journal of Mathematical Analysis and Optimization: Theory and Applications, 2019*(2), 631-643.

Abdollahi, H. (2020). An Adaptive Neuro-Based Fuzzy Inference System (ANFIS) for the Prediction of Option Price: The Case of the Australian Option Market. *International Journal of Applied Metaheuristic Computing (IJAMC), 11*(2), 99-117.

Akten, N. (2004). Analysis of shipping casualties in the Bosphorus. *The Journal of Navigation, 57*(3), 345-356.

Akyuz, E. (2015). A hybrid accident analysis method to assess potential navigational contingencies: The case of ship grounding. *Safety Science, 79*, 268-276. doi:10.1016/j.ssci.2015.06.019

Altan, Y. C., & Otay, E. N. (2018). Spatial mapping of encounter probability in congested waterways using AIS. *Ocean Engineering, 164*, 263-271.

Amrozowicz, M. D. (1996). *The quantitative risk of oil tanker groundings*. Retrieved from

Arifin, F., Hasanah, N., Irmawati, D., & Arifin, Z. (2020). *Smart System for Diagnosing Motorcycle Damage Using Adaptive Neuro-Fuzzy Inference System for Future Transportation.* Paper presented at the International Conference on Educational Research and Innovation (ICERI 2019).

Arimura, N., Yamada, K., Sugasawa, S., & Okano, Y. (1994). Development of Collisions Preventing Support System: Model of Evaluation Indices for Navigation. *The Journal of Japan Institute of Navigation, 91*, 195-201.

Arslan, O., & Turan, O. (2009). Analytical investigation of marine casualties at the Strait of Istanbul with SWOT–AHP method. *Maritime Policy & Management, 36*(2), 131-145.

Baran, A., Fişkin, R., & Kişi, H. (2018). A Research on Concept of Ship Safety Domain. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation, 12*.

Bilgiç, T., & Türkşen, I. B. (2000). Measurement of membership functions: theoretical and empirical work *Fundamentals of fuzzy sets* (pp. 195-227): Springer.

Bukhari, A. C., Gil lee, B., Tusseyeva, I., & Kim, Y.-G. (2013). An intelligent real-time multi-vessel collision risk assessment system from VTS view point based on fuzzy inference system. *Expert Systems with Applications, 40*(4), 1220-1230.

Cavallaro, F. (2015). A Takagi-Sugeno fuzzy inference system for developing a sustainability index of biomass. *Sustainability, 7*(9), 12359-12371.

Cavallaro, F., & Ciraolo, L. (2017). Design and implementation of a fuzzy inference model for mapping the sustainability of energy crops *Renewable and Alternative Energy: Concepts, Methodologies, Tools, and Applications* (pp. 657-678): IGI Global.

Chang, S.-J., Hsiao, D.-T., & Wang, W.-C. (2014). *AIS-based delineation and interpretation of ship domain models.* Paper presented at the OCEANS 2014-TAIPEI.

Chen, S., Ahmad, R., Lee, B.-G., & Kim, D. (2014). Composition ship collision risk based on fuzzy theory. *Journal of Central South University, 21*(11), 4296-4302. doi:10.1007/s11771-014-2428-z

Chen, Y., Yang, J., Zhang, Q., Guo, F., & Liu, Y. (2017). *Ship collision avoidance on the basis of 3-d model.* Paper presented at the Intelligent Transportation Engineering (ICITE), 2017 2nd IEEE International Conference on.

Coldwell, T. (1983). Marine traffic behaviour in restricted waters. *The Journal of Navigation, 36*(3), 430-444.

COWI. (2008). *Risk analysis for Sea traffic in the area around Bornholm.* (P-65775–002). Retrieved from Kongens Lyngby, Denmark:

Curtis, R. G. (1986). A ship collision model for overtaking. *Journal of the Operational Research Society, 37*(4), 397-406.

Davis, P., Dove, M., & Stockel, C. (1980). A computer simulation of marine traffic using domains and arenas. *The journal of Navigation, 33*(2), 215-222.

Davis, P., Dove, M., & Stockel, C. (1982). A computer simulation of multi-ship encounters. *The Journal of navigation, 35*(2), 347-352.

Dias, F. M., Antunes, A., Vieira, J., & Mota, A. (2006). A sliding window solution for the on-line implementation of the Levenberg–Marquardt algorithm. *Engineering Applications of Artificial Intelligence, 19*(1), 1-7.

Dinh, G. H., & Im, N.-K. (2016). The combination of analytical and statistical method to define polygonal ship domain and reflect human experiences in estimating dangerous area. *International Journal of e-Navigation and Maritime Economy, 4*, 97-108.

Eide, M. S., Endresen, Ø., Breivik, Ø., Brude, O. W., Ellingsen, I. H., Røang, K., . . . Brett, P. O. (2007). Prevention of oil spill from shipping by modelling of dynamic risk. *Marine Pollution Bulletin, 54*(10), 1619-1633.

EMSA. (2017a). *Annual Overview of Marine Casualties and Incidents 2017*. Retrieved from http://www.emsa.europa.eu/

EMSA. (2017b). *Marine Casualties And Incidents-Summary Overview 2011-2015*. Retrieved from http://www.emsa.europa.eu/

EMSA. (2019). *Annual Overview of Marine Casualties and Incidents 2019*. Retrieved from http://www.emsa.europa.eu/

Endoh, S. (1982). *Aircraft collision models.* Massachusetts Institute of Technology. (Doctoral dissertation)

Fachinotti, V., Anca, A., & Cardona, A. (2011). A method for the solution of certain problems in least squares. *Int J Numer Method Biomed Eng, 27*(4), 595-607.

Fan, Y.-t., Huang, L.-w., & Xu, X.-z. (2018). Study on the Early Warning Model of VTS Based on Dynamic Ship Domain. *DEStech Transactions on Computer Science and Engineering*(mso).

Ford, D. N., & Sterman, J. D. (1998). Expert knowledge elicitation to improve formal and mental models. *System Dynamics Review: The Journal of the System Dynamics Society, 14*(4), 309-340.

Fowler, T. G., & Sørgård, E. (2000). Modeling ship transportation risk. *Risk Analysis, 20*(2), 225-244.

Frandsen, A. G., Olsen, D. F., Lund, H. T., & Bach, P. E. (1991). *Evaluation of minimum bridge span openings applying ship domain theory*.

Friis-Hansen, P., & Simonsen, B. C. (2002). GRACAT: software for grounding and collision risk analysis. *Marine Structures, 15*(4-5), 383-401.

Fuji, J., & Tanaka, K. (1971). Traffic Capacity. *Journal of Navigation, 24*, 543-552.

Fujii, Y., Oshima, R., Yamanouchi, H., & Mizuki, N. (1974). Some factors affecting the frequency of accidents in marine traffic. *The Journal of Navigation, 27*(2), 239-247.

Fujii, Y., & Shiobara, R. (1971). The analysis of traffic accidents. *The Journal of Navigation, 24*(4), 534-543.

Fujii, Y., Tanaka, K., Watanabe, K., Yamada, K., & Seki, M. (1966). Effective Areas of Ships. *The Journal of the Nautical Society of Japan, 35*, 71-76. doi:10.9749/jina.35.0_71

Gale, H., & Patraiko, D. (2007). Improving navigational safety: Seaways.

Ghaghishpour, A., & Koochaki, A. (2020). An intelligent method for online voltage stability margin assessment using optimized ANFIS and associated rules technique. *ISA Transactions*.

Goerlandt, F., & Montewka, J. (2015). Maritime transportation risk analysis: Review and analysis in light of some foundational issues. *Reliability Engineering & System Safety, 138*, 115-134. doi:10.1016/j.ress.2015.01.025

Goerlandt, F., Montewka, J., Kuzmin, V., & Kujala, P. (2015). A risk-informed ship collision alert system: Framework and application. *Safety Science, 77*, 182-204. doi:10.1016/j.ssci.2015.03.015

Goodwin, E. M. (1975). A statistical study of ship domains. *The Journal of navigation, 28*(3), 328-344.

Hansen, M. G., Jensen, T. K., Lehn-Schiøler, T., Melchild, K., Rasmussen, F. M., & Ennemark, F. (2013). Empirical Ship Domain based on AIS Data. *Journal of Navigation, 66*(06), 931-940. doi:10.1017/s0373463313000489

Hansen, P. F., & Pedersen, P. T. (1997). Risk analysis of conventional and solo watch keeping.

Hara, K., & Nakamura, S. (1995). A comprehensive assessment system for the maritime traffic environment. *Safety Science, 19*(2-3), 203-215.

Hwang, S., Kobayashi, E.-i., Wakabayashi, N., & Im, N. (2016). A New Risk Evaluation Model for Safety Management on an Entire Ship Route. *TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation, 10*(1), 93-98. doi:10.12716/1001.10.01.10

IHO. (2017). S-57, S-63 and S-52: The latest IHO Standards and what they mean. Retrieved from https://www.admiralty.co.uk/news/blogs/s-57-and-the-latest-iho-standards

IHO. (2019). *S-62 - List of Data Producer Codes*. Retrieved from http://www.iho-ohi.net/s62/pdfExport/pacPDFExport.php

IMO Performance Standards for Shipborne Voyage Data Recorders (VDRs) IMO Resolution A.861(20) C.F.R. (1997).

IMO. (2001). *IMO Resolution A.917 (22), Guidelines for the Onboard Operational Use of Shipborne Automatic Identification Systems (AIS)*. Retrieved from

IMO. (2007). *Adoption of the revised performance standards for integrated navigation systems (INS) 83/23/Add.3-ANNEX 30.* . Retrieved from

IMO. (2015). *IMO Resolution A.1106 (29) Revised Guidelines for the Onboard Operational Use of Shipborne Automatic Identification System* Retrieved from

IMO. (2017). S-57, S-63 and S-52: The latest IHO Standards and what they mean. Retrieved from https://www.admiralty.co.uk/news/blogs/s-57-and-the-latest-iho-standards

ITU. (1998). M.1371 : Technical characteristics for an automatic identification system using time-division multiple access in the VHF maritime mobile band.

James, M. (1986). Modelling the decision process in computer simulation of ship navigation. *The Journal of Navigation, 39*(1), 32-48.

Jingsong, Z., Zhaolin, W., & Fengchen, W. (1993). Comments on ship domains. *The Journal of Navigation, 46*(3), 422-436.

Kaneko, F. (2002). Methods for probabilistic safety assessments of ships. *Journal of Marine Science and Technology, 7*(1), 1-16.

Kao, S.-L., Lee, K.-T., Chang, K.-Y., & Ko, M.-D. (2007). A fuzzy logic method for collision avoidance in vessel traffic service. *The Journal of Navigation, 60*(1), 17-31.

Karlsson, M., Rasmussen, F. M., Frisk, L., & Ennemark, F. (1998). Verification of ship collision frequency model. *Ship collision analysis*, 117-121.

Kijima, K., & Furukawa, Y. (2001). Design of Automatic Collision Avoidance System Using Fuzzy Inference. *IFAC Proceedings Volumes, 34*(7), 65-70. doi:10.1016/s1474-6670(17)35060-7

Kijima, K., & Furukawa, Y. (2003). Automatic collision avoidance system using the concept of blocking area. *IFAC Proceedings Volumes, 36*(21), 223-228. doi:10.1016/s1474-6670(17)37811-4

Klanac, A., Duletic, T., Erceg, S., Ehlers, S., Goerlandt, F., & Frank, D. (2010). *Environmental risk of collisions in the enclosed European waters: Gulf of Finland, Northern Adriatic and the implications for tanker design.* Paper presented at the 5th International Conference on Collision and Grounding of Ships. Aalto University, Espoo, Finland.

KONG, F.-c., HU, Q.-y., & CHEN, Y.-l. (2004). The Design of Ship Collision Simulation System Based on VDR Playback Data [J]. *Navigation of China, 2*, 25-28.

Koto, J. (2018). Development of Automatic Identification System (AIS) for Vessels Traffic Monitoring in the Strait of Singapore and Batam Waterways. *Science and Engineering, 51*.

Kristiansen, S. (2010). A BBN approach for analysis of maritime accident scenarios. *Proceedings of the ESREL, Rhodes, Greece*.

Kristiansen, S. (2013). *Maritime transportation: safety management and risk analysis*: Routledge.

Kujala, P., Hänninen, M., Arola, T., & Ylitalo, J. (2009). Analysis of the marine traffic safety in the Gulf of Finland. *Reliability Engineering & System Safety, 94*(8), 1349-1357. doi:10.1016/j.ress.2009.02.028

Kum, S., Fuchi, M., & Furusho, M. (2006). Analysing of maritime accidents by approaching method for minimizing human error. *Proceedings of IAMU AGA-7,"Globalization and MET," Part, 2*, 392-409.

Lavasani, S. M., Zendegani, A., & Celik, M. (2015). An extension to fuzzy fault tree analysis (FFTA) application in petrochemical process industry. *Process Safety and Environmental Protection, 93*, 75-88.

Lee, K. H. (2004). *First course on fuzzy theory and applications* (Vol. 27): Springer Science & Business Media.

Li, B., & Pang, F.-W. (2013). An approach of vessel collision risk assessment based on the D–S evidence theory. *Ocean Engineering, 74*, 16-21.

Li, S., Meng, Q., & Qu, X. (2012). An overview of maritime waterway quantitative risk assessment models. *Risk Analysis: An International Journal, 32*(3), 496-512.

Li, S., Meng, Q., & Qu, X. (2012). An overview of maritime waterway quantitative risk assessment models. *Risk Anal, 32*(3), 496-512. doi:10.1111/j.1539-6924.2011.01697.x

Liu, J., Zhou, F., Li, Z., Wang, M., & Liu, R. W. (2015). Dynamic Ship Domain Models for Capacity Analysis of Restricted Water Channels. *Journal of Navigation, 69*(03), 481-503. doi:10.1017/s0373463315000764

Liu, L., & Zhang, P. (2010). Study on maritime transportation safety pre-warning scheme of Yangtze river. *Journal of Transportation Information and Safety, 4*, 116-118.

Liu, Y.-H., & Shi, C.-J. (2005). *A fuzzy-neural inference network for ship collision avoidance.* Paper presented at the Machine Learning and Cybernetics, 2005. Proceedings of 2005 International Conference on.

Macduff, T. (1974). The probability of vessel collisions. *Ocean Industry, 9*(9).

Mamdani, E. H. (1976). *Application of fuzzy logic to approximate reasoning using linguistic synthesis.* Paper presented at the Proceedings of the sixth international symposium on Multiple-valued logic.

Marquardt, D. W. (1963). An algorithm for least-squares estimation of nonlinear parameters. *Journal of the society for Industrial and Applied Mathematics, 11*(2), 431-441.

Mazaheri, A., Montewka, J., & Kujala, P. (2013). Modeling the risk of ship grounding—a literature review from a risk management perspective. *WMU Journal of Maritime Affairs, 13*(2), 269-297. doi:10.1007/s13437-013-0056-3

Mazaheri, A., Montewka, J., & Kujala, P. (2014). Modeling the risk of ship grounding—a literature review from a risk management perspective. *WMU journal of maritime affairs, 13*(2), 269-297.

Mazaheri, A., & Ylitalo, J. (2010). *Comments on geometrical modeling of ship grounding.* Paper presented at the 5th International Conference on Collision and Grounding of Ships (ICCGS).

Mehrani, M., Attarzadeh, I., & Hosseinzadeh, M. Deep-learning based forecasting sampling frequency of biosensors in wireless body area networks. *Journal of Intelligent & Fuzzy Systems*(Preprint), 1-33.

Montewka, J., Ehlers, S., Goerlandt, F., Hinz, T., Tabri, K., & Kujala, P. (2014). A framework for risk assessment for maritime transportation systems—A case study for open sea collisions involving RoPax vessels. *Reliability Engineering & System Safety, 124*, 142-157. doi:10.1016/j.ress.2013.11.014

Montewka, J., Goerlandt, F., & Kujala, P. (2012). Determination of collision criteria and causation factors appropriate to a model for estimating the probability of maritime accidents. *Ocean Engineering, 40*, 50-61. doi:10.1016/j.oceaneng.2011.12.006

Montewka, J., Hinz, T., Kujala, P., & Matusiak, J. (2010). Probability modelling of vessel collisions. *Reliability Engineering & System Safety, 95*(5), 573-589. doi:10.1016/j.ress.2010.01.009

Montewka, J., Krata, P., Goerlandt, F., Mazaheri, A., & Kujala, P. (2011). Marine traffic risk modelling–an innovative approach and a case study. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 225*(3), 307-322.

Morsi, I., Zaghloul, M., & Essam, N. (2010). *Future voyage data recorder based on multi-sensors and human machine interface for marine accident.* Paper presented at the ICCAS 2010.

Oh, J.-H., Kim, K.-i., & Jeong, J.-S. (2015). A Study on the Risk Analysis based on the Trajectory of Fishing Vessels in the VTS Area. *International Journal of e-Navigation and Maritime Economy, 2*, 38-46. doi:10.1016/j.enavi.2015.06.004

Otto, S., Pedersen, P. T., Samuelides, M., & Sames, P. C. (2002). Elements of risk analysis for collision and grounding of a RoRo passenger ferry. *Marine Structures, 15*(4-5), 461-474.

Ozturk, U., & Cicek, K. (2019). Individual collision risk assessment in ship navigation: A systematic literature review. *Ocean Engineering, 180*, 130-143.

Panigrahi, D., & Mujumdar, P. (2000). Reservoir operation modelling with fuzzy logic. *Water Resources Management, 14*(2), 89-109.

Park, G.-k., Hong, T., Kim, D.-y., & Jeong, J.-s. (2012). *Implementation of an intelligent system for identifying vessels exhibiting abnormal navigation patterns.* Paper presented at the Soft Computing and Intelligent Systems (SCIS) and 13th International Symposium on Advanced Intelligent Systems (ISIS), 2012 Joint 6th International Conference on.

Pedersen, P. T. (1995). Collision and grounding mechanics. *Proceedings of WEMT, 95*(1995), 125-157.

Pedersen, P. T. (2010). Review and application of ship collision and grounding analysis procedures. *Marine Structures, 23*(3), 241-262. doi:10.1016/j.marstruc.2010.05.001

Piccinelli, M., & Gubian, P. (2013). Modern ships Voyage Data Recorders: A forensics perspective on the Costa Concordia shipwreck. *Digital investigation, 10*, S41-S49.

Pietrzykowski, Z. (1999). *Ship fuzzy domain in assessment of navigational safety in restricted areas.* Paper presented at the Proc. of 3rd Navigational Symposium.

Pietrzykowski, Z. (2001). The Analysis of a Ship Fuzzy Domain in a Restricted Area. *IFAC Proceedings Volumes, 34*(7), 45-50. doi:10.1016/s1474-6670(17)35057-7

Pietrzykowski, Z. (2008). Ship's Fuzzy Domain – a Criterion for Navigational Safety in Narrow Fairways. *Journal of Navigation, 61*(03). doi:10.1017/s0373463308004682

Pietrzykowski, Z., Magaj, J., & Wielgosz, M. (2018). Navigation decision support for sea-going ships in port approach areas. *Zeszyty Naukowe Akademii Morskiej w Szczecinie*.

Pratiwi, E., Artana, K. B., & Dinariyana, A. (2017). Fuzzy Inference System for Determining Collision Risk of Ship in Madura Strait Using Automatic Identification System. *World Academy of Science, Engineering and Technology, International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 11*(2), 401-405.

Rambøll. (2006). *Navigational safety in the Sound between Denmark and Sweden (Øresund)*. Retrieved from Virum Danmark:

Rao, M. E., & Rao, S. G. (2014). Expert System for Heart Problems. *International Journal of Science, Engineering and Computer Technology, 4*(10), 266.

Rawson, A., Rogers, E., Foster, D., & Phillips, D. (2014). Practical application of domain analysis: port of London case study. *The Journal of Navigation, 67*(2), 193-209.

Rowe, W. D. (1994). Understanding uncertainty. *Risk analysis, 14*(5), 743-750.

Samuelides, M., Ventikos, N., & Gemelos, I. (2009). Survey on grounding incidents: Statistical analysis and risk assessment. *Ships and Offshore Structures, 4*(1), 55-68.

Selvam, K., & Sahoo, S. (2020). An Overview of Neuro-Fuzzy-Based DTC for Matrix Converter-Fed PMSM Drives *Computing Algorithms with Applications in Engineering* (pp. 77-85): Springer.

Senol, Y. E., Aydogdu, Y. V., Sahin, B., & Kilic, I. (2015). Fault tree analysis of chemical cargo contamination by using fuzzy approach. *Expert Systems with Applications, 42*(12), 5232-5244.

Senol, Y. E., & Sahin, B. (2016). A novel real-time continuous fuzzy fault tree analysis (RC-FFTA) model for dynamic environment. *Ocean Engineering, 127*, 70-81.

Simonsen, B. C. (1997). Mechanics of ship grounding. *Technical University of Denmark, Ph. D. thesis*.

Singh, H., & Lone, Y. A. (2020). Fuzzy Inference Systems *Deep Neuro-Fuzzy Systems with Python* (pp. 93-127): Springer.

Smierzchalski, R. (2000). Ships' domains as a collision risk at sea in the evolutionary trajectory planning. *WIT Transactions on Ecology and the Environment, 45*.

Smierzchalski, R., & Michalewicz, Z. (2000). Modeling of ship trajectory in collision situations by an evolutionary algorithm. *IEEE Transactions on Evolutionary Computation, 4*(3), 227-241.

Śmierzchalski, R., Weintrit, A., Smierzchalski, R., & Weintrit, A. (1999). *Domains of navigational objects as an aid to route planning in collision situation at sea.* Paper presented at the Proc. of 3rd Navigational Symposium, Gdynia.

SOLAS Chapter V-Safety of Navigation, Regulation 19 - Carriage requirements for shipborne navigational systems and equipment C.F.R. (1995).

Szlapczynski, R. (2006). A Unified Measure Of Collision Risk Derived From The Concept Of A Ship Domain. *Journal of Navigation, 59*(03). doi:10.1017/s0373463306003833

Szlapczynski, R., & Szlapczynska, J. (2016). An analysis of domain-based ship collision risk parameters. *Ocean Engineering, 126*, 47-56. doi:10.1016/j.oceaneng.2016.08.030

Szlapczynski, R., & Szlapczynska, J. (2017). A Framework of a Ship Domain-based Collision Alert System. 183-189. doi:10.1201/9781315099132-32

Szlapczynski, R., & Szlapczynska, J. (2017a). A method of determining and visualizing safe motion parameters of a ship navigating in restricted waters. *Ocean Engineering, 129*, 363-373.

Szlapczynski, R., & Szlapczynska, J. (2017b). Review of ship safety domains: Models and applications. *Ocean Engineering, 145*, 277-289.

Tam, C., Bucknall, R., & Greig, A. (2009). Review of Collision Avoidance and Path Planning Methods for Ships in Close Range Encounters. *Journal of Navigation, 62*(03), 455. doi:10.1017/s0373463308005134

Tanaka, K. (1994). *Advanced fuzzy control of a trailer type mobile robot-stability analysis and model-based fuzzy control.* Paper presented at the Tools with Artificial Intelligence, 1994. Proceedings., Sixth International Conference on.

Transas. (2012). NTPRO 5000 (Version 5.25) [Computer software]: Transas. Bridge Simulator.

Uğurlu, Ö., Köse, E., Yıldırım, U., & Yüksekyıldız, E. (2015). Marine accident analysis for collision and grounding in oil tanker using FTA method. *Maritime Policy & Management, 42*(2), 163-185.

Uğurlu, Ö., Yıldırım, U., & Başar, E. (2015). Analysis of grounding accidents caused by human error. *Journal of Marine Science and Technology, 23*(5), 748-760.

Ulusçu, Ö. S., Özbaş, B., Altıok, T., & Or, İ. (2009). Risk analysis of the vessel traffic in the strait of Istanbul. *Risk Analysis: An International Journal, 29*(10), 1454-1472.

UNCTAD. (2017). *Review of maritime transport 2017.* Paper presented at the Proceedings of the United Nations Conference on Trade and Development.

Van der Tak, C., & Spaans, J. (1977). A Model for Calculating a Maritime Risk Criterion Number. *The Journal of Navigation, 30*(2), 287-295.

Wang, N. (2010). An Intelligent Spatial Collision Risk Based on the Quaternion Ship Domain. *Journal of Navigation, 63*(04), 733-749. doi:10.1017/s0373463310000202

Wang, N. (2012). A Novel Analytical Framework for Dynamic Quaternion Ship Domains. *Journal of Navigation, 66*(02), 265-281. doi:10.1017/s0373463312000483

Wang, N., Meng, X., Xu, Q., & Wang, Z. (2009). A Unified Analytical Framework for Ship Domains. *Journal of Navigation, 62*(04), 643. doi:10.1017/s0373463309990178

Wang, Y. (2012). *An Empirical Model of Ship Domain for Navigation in Restricted Waters.* Retrieved from https://scholarbank.nus.edu.sg/handle/10635/36604 (Doctoral dissertation)

Wang, Y., & Chin, H.-C. (2015). An Empirically-Calibrated Ship Domain as a Safety Criterion for Navigation in Confined Waters. *Journal of Navigation, 69*(02), 257-276. doi:10.1017/s0373463315000533

Weng, J., Meng, Q., & Qu, X. (2012). Vessel collision frequency estimation in the Singapore Strait. *The Journal of Navigation, 65*(2), 207-221.

Yıldırım, U., Başar, E., & Uğurlu, Ö. (2019). Assessment of collisions and grounding accidents with human factors analysis and classification system (HFACS) and statistical methods. *Safety Science, 119*, 412-425.

Zadeh, L. A. (1965). Fuzzy sets. *Information and control, 8*(3), 338-353.

Zadeh, L. A. (1988). Fuzzy logic. *Computer, 21*(4), 83-93.

Zaman, M., Kobayashi, E., Wakabayashi, N., Khanfir, S., Pitana, T., & Maimun, A. (2014). Fuzzy FMEA model for risk evaluation of ship collisions in the Malacca Strait: based on AIS data. *Journal of Simulation, 8*(1), 91-104.

Zhang, J., Yan, X., Chen, X., Sang, L., & Zhang, D. (2012). A novel approach for assistance with anti-collision decision making based on the International Regulations for Preventing Collisions at Sea. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 226*(3), 250-259. doi:10.1177/1475090211434869

Zhang, W., Goerlandt, F., Montewka, J., & Kujala, P. (2015). A method for detecting possible near miss ship collisions from AIS data. *Ocean Engineering, 107*, 60-69. doi:10.1016/j.oceaneng.2015.07.046

Zhao, J., & Bose, B. K. (2002). *Evaluation of membership functions for fuzzy logic controlled induction motor drive.* Paper presented at the IEEE 2002 28th Annual Conference of the Industrial Electronics Society. IECON 02.

Zhou, D., & Zheng, Z. Dynamic Fuzzy Ship Domain Considering the Factors of Own Ship and Other Ships. *The Journal of Navigation*, 1-16.

Zhou, X.-Y., Liu, Z.-J., Wang, F.-W., & Ni, S.-K. (2018). *Collision risk identification of autonomous ships based on the synergy ship domain.* Paper presented at the 2018 Chinese Control And Decision Conference (CCDC).

Zhu, X., Xu, H., & Lin, J. (2001). Domain and its model based on neural networks. *The Journal of Navigation, 54*(1), 97-103.

CURRICULUM VITAE

Name Surname **: Yunus Emre ŞENOL**

Place and Date of Birth **: 03.08.1988 – ANKARA**

E-Mail **: senoly@itu.edu.tr**

EDUCATION **:**

- **B.Sc.** **:** 2011, Istanbul Technical University, Maritime Faculty, Maritime Transportation and Management Engineering.
- **M.Sc.** **:** 2014, Istanbul Technical University, Maritime Faculty, Maritime Transportation and Management Engineering.

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2011-2013 Oceangoing Second Officer on Chemical Tankers
- 2013-2019 Research Assistant at Istanbul Technical University
- 2019- Lecturer at Istanbul Technical University

PUBLICATIONS, PRESENTATIONS AND PATENTS ON THE THESIS:

- **Senol, Y. E.**, & Sahin, B. (2016). A Novel Real-Time Continuous Fuzzy Fault Tree Analysis (RC-FFTA) Model for Dynamic Environment. Ocean Engineering, 127, 70-81.

OTHER PUBLICATIONS, PRESENTATIONS AND PATENTS:

- Atar, F., Aydoğdu, Y. V., Duru, O., **Senol, Y. E.,** & Gökdeniz, A. (2013). Advantages of Short Sea Shipping and its Importance on Combined Transportation, Journal of Dokuz Eylul Universitesi Denizcilik Fakültesi 5(1), 77-94.
- Aydogdu Y.V., Gulluce **Y., Senol Y. E.** 2013 *A Study on Early Fire Detection System for Port and Shipyard Areas*, 1st International Conference Black Sea Association of Maritime Institution, Novorossiysk, Russia 25-27 June 2013
- **Senol, Y. E.,** Sahin, B., Aydogdu Y.V., Kum S., Duru O., Gunes E. 2013 *Coaster Fleet Design and Selection in the Coastal Maritime Transport*, The Global Reach of Industrial Engineering, Istanbul June 26-28, 2013
- Kilic I., **Senol Y. E.** 2013: *Struggle Ways of late years with piracy and Security Approach of Turkey*, National Marine Congress, Istanbul November 11, 2013
- **Senol, Y. E**., Şahin, B., & Kum, S. (2014). Marine Accident Analysis by Using Pairwise Comparison. Journal of ETA Maritime Science, 1(2), 59-64.
- Sahin, B., & **Senol, Y. E. (2015).** A novel process model for marine accident analysis by using generic fuzzy-AHP algorithm. The Journal of Navigation, 68(1), 162-183**.**
- **Senol, Y. E**., Aydogdu, Y. V., Sahin, B., & Kilic, I. (2015). Fault tree analysis of chemical cargo contamination by using fuzzy approach. Expert Systems with Applications, 42(12), 5232-5244.
- Sahin, B., **Senol, Y. E.,** Bulut, E., & Duru, O. (2015). Optimizing technology selection in maritime logistics. Research in Logistics & Production, 5.
- Gökçek, V., & **Senol, Y. E. (2018).** Efficiency Analysis of Mediterranean Container Ports. Journal of ETA Maritime Science, 6(2), 129-140.
- Kuzu A. C., **Senol Y. E.** and Arslan Ö.. (2018). Bağlama Operasyonları Esnasında Kopan Halat Yaralanmalarının Bulanık Hata Ağacı Yöntemi ile Analizi Journal of ETA Maritime Science Vol. 6(3), 215-227.