

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**RISK ASSESSMENT OF BITUMEN TANKER OPERATIONS USING
INTUITIONISTIC FUZZY FAULT TREE ANALYSIS**



M.Sc. THESIS

Batur Alp ÖZDEMİR

Department of Maritime Transportation Engineering

Maritime Transportation Engineering Programme

JUNE 2025

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

**RISK ASSESSMENT OF BITUMEN TANKER OPERATIONS USING
INTUITIONISTIC FUZZY FAULT TREE ANALYSIS**



M.Sc. THESIS

**Batur Alp ÖZDEMİR
(512221032)**

Department of Maritime Transportation Engineering

Maritime Transportation Engineering Programme

Thesis Advisor: Assoc. Prof. Dr. Yunus Emre ŞENOL

JUNE 2025

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

**BITÜM TANKERİ OPERASYONLARINDA SEZGİSEL BULANIK HATA
AĞACI ANALİZİ KULLANILARAK RİSK DEĞERLENDİRİLMESİ**

YÜKSEK LİSANS TEZİ

**Batur Alp ÖZDEMİR
(512221032)**

Deniz Ulaştırma Mühendisliği Anabilim Dalı

Deniz Ulaştırma Mühendisliği Programı

Tez Danışmanı: Assoc. Prof. Dr. Yunus Emre ŞENOL

HAZİRAN 2025

Batur Alp ÖZDEMİR, a M.Sc. student of ITU Graduate School, student ID 512221032, successfully defended the thesis entitled “RISK ASSESSMENT OF BITUMEN TANKER OPERATIONS USING INTUITIONISTIC FUZZY FAULT TREE ANALYSIS”, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Assos. Prof. Dr. Yunus Emre ŞENOL**
Istanbul Technical University

Jury Members : **Dr. Cenk AY**
Istanbul Technical University

Dr. Alper SEYHAN
Zonguldak Bulent Ecevit University

Date of Submission : 30 May 2025
Date of Defence : 19 June 2025



To my daughter Dora and my wife Simge, who supported me at every moment,

With my deepest thanks to my esteemed advisor Yunus Emre, who generously offered his guidance and friendship from beginning to end,

To the Ditaş Tanker family, who did not withhold their contributions and efforts,



FOREWORD

This thesis aims to present an original risk assessment approach for bitumen tanker operations, a specialized field within maritime transportation. The high temperature requirements, viscous nature, and operational challenges of bitumen have necessitated a multidimensional analysis of the transportation process. In this context, the study seeks to contribute to the academic literature and provide meaningful outcomes for practitioners through the intuitive fuzzy fault tree method.

I would like to express my sincere gratitude to my esteemed thesis advisor, Assoc. Prof. Dr. Yunus Emre ŞENOL, whose guidance illuminated every stage of this process and shaped the course of my work. His mentorship not only enhanced the academic quality of this study but also enriched my perspective on the subject.

I extend my thanks to the industry experts from Ditaş Tanker for their generous sharing of experience and valuable insights during the development of this thesis, particularly for their support during the evaluation phase. I am also grateful to the academicians who contributed to the collection and interpretation of expert opinions on intuitive fuzzy systems.

I would like to thank my family for their unwavering moral support throughout this journey, and my heartfelt appreciation goes to my wife Simge and my daughter Dora for their patience and understanding. I sincerely acknowledge my brother, Chief Engineer Baturay ÖZDEMİR my companion in life and career, for his constant presence and support. I also extend my thanks to the institutions and organizations that provided assistance in data acquisition, literature support, and technical documentation.

It is my hope that this thesis will not only contribute academically but also support safer, more sustainable, and more predictable practices in bitumen tanker operations.

May 2025

Batur Alp ÖZDEMİR
Oceangoing Master &
Superintendent

TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	ix
TABLE OF CONTENTS	xi
ABBREVIATIONS	xiii
SYMBOLS	xv
LIST OF TABLES	xvii
LIST OF FIGURES	xix
SUMMARY	xxi
ÖZET	xxiii
1. INTRODUCTION	1
1.1 Purpose of the Thesis	3
1.2 Literature Review	4
1.2.1 Description of bitumen.....	4
1.2.2 Associated details of the bitumen regarding health and environment	8
1.2.3 Transportation methods of the bitumen	11
1.3 Specification and Handling of the Bitumen	12
2. METHODOLOGY	21
2.1 Fault Tree Analysis	22
2.1.1 Representation of logic gates and calculation of their probabilities	24
2.1.1.1 Probability calculation for the AND Gate.....	24
2.1.1.2 Probability calculation for the OR Gate	24
3. CASE STUDY	27
3.1 General Structure of the Fault Tree.....	27
3.2 Definition and Classification of Basic Events.....	27
3.3 Fuzzy Scale Construction and Conversation.....	28
3.4 Evaluation Methodology and Calculation Process.....	30
3.5 Review of Case Study	32
3.5.1 Explanation of the fault tree structure.....	32
3.5.1.1 Process independent failures	33
3.5.1.2 During loading operation.....	33
3.5.1.3 During voyage	33
3.5.1.4 During discharging operation.....	33
3.5.1.5 Top event (TE)	37
3.5.1.6 IE1 – Process independent failures	37
3.5.1.7 IE2 – Failures during voyage	38
3.5.1.8 IE3 –Loading operation failures.....	39
3.5.1.9 IE4 – Discharge operation failures.....	39
3.6 Logic Gates and Failure Relationships.....	40
3.7 Crisp Failure Probability	40
3.8 Failure Probability (FP).....	42
3.8.1 Events with the highest FP values.....	42

3.8.2 Events with the lowest FP values	44
3.9 MCS – Probability	44
3.10 The Fussell-Vesely Importance Measure	46
4. RESULTS AND DISCUSSIONS	49
5. CONCLUSIONS AND RECOMMENDATIONS	55
REFERENCES	57
CURRICULUM VITAE	59



ABBREVIATIONS

AP	: Area Protected
BIS	: Ballast Water Information System
BWM	: Ballast Water Management
CC	: Cargo Control
CLP	: Classification, Labelling, Packaging
DWT	: Deadweight Tonnage
E0	: Unattended Machinery Space
ECA	: Emission Control Area
EMR	: Emission Reduction Measure
ESP	: Enhanced Survey Program
FTA	: Fault Tree Analysis
GHS	: Globally Harmonised System of Classification and Labelling of Chemicals
HL	: High Loading
IARC	: International Agency for Research on Cancer
IFFTA	: Intuitionistic Fuzzy Fault Tree Analysis
IBC Code	: The International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk
IMDG	: International Maritime Dangerous Goods Code
IMO	: International Maritime Organization
LC50	: Lethal Concentration 50%
MC	: Medium Curing
MS	: Medium Setting
NAUT(OC)	: Nautical Operational Control
PAH	: Polycyclic Aromatic Hydrocarbons
PMB	: Polymer Modified Bitumen
RC	: Rapid Curing
RS	: Rapid Setting
SC	: Slow Curing
SOLAS	: International Convention for the Safety of Life at Sea

SS : Slow Setting
TMON : Tank Monitoring
VOC : Volatile Organic Compounds
VCS : Vapor Control System



SYMBOLS

α	: Expert confidence level (α -cut level in fuzzy logic)
β	: Degree of uncertainty / Confidence coefficient
δ	: Tolerance level or sensitivity parameter
λ	: Failure rate
$\mu(x)$: Membership degree of element x in a fuzzy set
$\nu(x)$: Non-membership degree of element x in an intuitionistic fuzzy set
$\pi(x)$: Uncertainty degree of element
$P(T)$: Probability of the top event occurrence
$P(i)$: Probability of the i -th intermediate event
$R(t)$: Reliability function at time t
Θ	: Set of all basic events used in the fault tree
Δt	: Time interval
Σ	: Summation operator — used for aggregating component effects
\oplus	: Intuitionistic fuzzy aggregation operator
\otimes	: Logical product or multiplication of relative importance coefficient



LIST OF TABLES

	<u>Page</u>
Table 3.1 : Anonymous consulted expert and their weights.	28
Table 3.2 : IFNs and corresponding linguistic expressions.	29
Table 3.3 : Experts' judgement for BE49.....	29
Table 3.4 : Expectancy evaluation values of experts for BE49.	29
Table 3.5 : Similarity matrix of experts' opinion for BE49.....	30
Table 3.6 : Average agreement, relative agreement degrees for BE49.	30
Table 3.7 : Aggregation of experts' opinions on BE49.	30
Table 3.8 : BE's of the fault tree.	36



LIST OF FIGURES

	<u>Page</u>
Figure 1.1 : Bitumen production in Türkiye (in thousand tonnes).....	31
Figure 3.1 : Operational fault tree in bitumen tanker operations	35
Figure 3.2 : Calculated CFP values for each BE.....	40
Figure 3.3 : Failure probability calculations	43
Figure 3.4 : MCS Probabilities of the BE's	45
Figure 3.5 : FVIM values.....	47





RISK ASSESSMENT OF BITUMEN TANKER OPERATIONS USING INTUITIONISTIC FUZZY FAULT TREE ANALYSIS

SUMMARY

This thesis focuses on the risk profile of bitumen tanker operations, which require specialized engineering solutions due to the high temperature requirements and viscous nature of the cargo. Transporting bitumen involves maintaining strict thermal parameters throughout the entire process, demanding a multidimensional assessment of technical, environmental, and human-related factors. In this context, the potential failure types that may occur during loading, navigation, and discharge operations onboard bitumen carriers have been analyzed through a systematic and structured approach.

The challenges encountered in bitumen tanker operations are not limited to technical failures but can also lead to significant environmental consequences, safety hazards, and economic losses. For this reason, the study examines not only the root causes of mechanical failures but also the broader systemic implications, incorporating issues such as heat loss, line blockages, human errors, and procedural deviations into the analysis. Each operational phase of the tanker is modeled through interconnected fault chains and evaluated using an intuitionistic fuzzy logic structure to produce a more inclusive and realistic analysis.

In this study, the Intuitionistic Fuzzy Fault Tree Analysis (IFFTA) method, known for its effectiveness in modeling uncertainty in complex decision environments, was employed. Unlike conventional fault tree analysis, IFFTA allows for the integration of expert intuition and partial judgments, offering a more flexible and inclusive framework for risk assessment. Supported by literature review, field observations, and expert interviews, the fault tree model was structured around top, intermediate, and basic event levels. The resulting fault tree represents each link in the operational chain of the bitumen tanker and enables a more accurate identification of root causes.

The developed fault tree model includes 67 distinct basic events related to bitumen tanker operations. It was submitted to 10 domain experts with extensive field

experience and niche technical knowledge. Each expert was asked to assess the relative importance of each event using a 7-level intuitionistic scale, structuring their evaluations according to the conventional understanding of risk as the product of frequency and severity. This methodology ensured that expert assessments were grounded in both intuition and technical logic. The fact that all consulted experts had direct, hands-on experience with bitumen tanker operations significantly enhanced the reliability and practical relevance of the collected data.

The findings revealed that the most critical failures in bitumen tanker operations stem not primarily from technical breakdowns but from human factors and organizational deficiencies. Key issues included disruptions in thermal control, degraded insulation systems, insufficient preparedness for emergency scenarios, and inconsistent procedural compliance. Accordingly, strategic recommendations were developed focusing on personnel training, preventive maintenance planning, standard operating procedures, and the formulation of scenario-based emergency action plans.

Additionally, elements such as vessel design, insulation efficiency, heating system reliability, and environmental safety were evaluated through a multi-dimensional risk matrix. The study emphasizes the necessity of addressing technical reliability and human performance as interdependent factors, aiming not only to analyze existing risks but also to promote a proactive safety culture in the bitumen transport industry.

In conclusion, this thesis provides a comprehensive and practical risk assessment model that contributes to both academic literature and real-world maritime operations. The analysis offers valuable insights for maritime companies and stakeholders to develop safer and more efficient strategies for managing the complex challenges of bitumen tanker operations.

BITÜM TANKERİ OPERASYONLARINDA SEZGİSEL BULANIK HATA AĞACI YÖNTEMİYLE RİSK DEĞERLENDİRİLMESİ

ÖZET

Bu tez çalışması, yüksek sıcaklık gereksinimi ve viskoz yapısı nedeniyle taşıma sürecinde özel mühendislik çözümleri gerektiren bitüm tanker operasyonlarının risk profiline odaklanmaktadır. Bitüm, taşıma sırasında sıcaklığın belirli sınırlar içinde tutulmasını zorunlu kılmakta; bu durum, operasyonun her aşamasında teknik, çevresel ve insani faktörlerin karmaşık bir etkileşim içinde değerlendirilmesini gerekli kılmaktadır. Bu bağlamda, bitüm taşıyan gemilerde yükleme, seyir ve tahliye gibi temel operasyonel süreçlerde karşılaşılabilecek hata türleri sistematik bir yaklaşımla analiz edilmiştir.

Bitüm tanker operasyonlarında yaşanan problemler yalnızca teknik arızalarla sınırlı kalmayıp, çevresel etkiler, insan güvenliği ve ekonomik kayıplar gibi çok boyutlu sonuçlara yol açabilmektedir. Bu nedenle çalışmada, yalnızca arızaların fiziksel sonuçları değil, bu sonuçların sistemsel yansımaları da ele alınmış; ısı kaybı, donma, tahliye hatlarında tıkanma gibi fiziksel sorunlar kadar, operatör hataları, eksik eğitim ve prosedürel sapmalar da risk matrisine dahil edilmiştir. Gemi operasyonlarının tüm aşamaları, birbiriyle bağlantılı hata zincirleri üzerinden modellenmiş ve bu modeller sezgisel bulanık mantık yapısıyla değerlendirilerek daha kapsayıcı bir analiz elde edilmiştir.

Tezde, belirsizlik içeren karar ortamlarını modellemede güçlü bir yöntem olan Sezgisel Bulanık Hata Ağacı Analizi (Intuitionistic Fuzzy Fault Tree Analysis IFFTA) kullanılmıştır. Bu yöntem, klasik hata ağacı analizine kıyasla daha esnek bir yapı sunmakta ve uzman görüşlerinden elde edilen sezgisel bilgilerin karar süreçlerine entegre edilmesine olanak tanımaktadır. Literatür taraması, saha gözlemleri ve uzman mülakatlarıyla desteklenen analiz sürecinde; operasyonel hatalar "top event", "intermediate event" ve "basic event" yapıları üzerinden modellenmiş ve her bir operasyonel halkadaki arıza türleri ayrı ayrı değerlendirilmiştir.

Geliştirilen hata ağacı modeli, bitüm tanker operasyonlarında karşılaşılabilecek 67 adet temel olayı (Basic Event) içerecek şekilde yapılandırılmış ve değerlendirme için alanında yetkin, saha tecrübesi yüksek 10 uzmanın görüşüne sunulmuştur. Uzmanlardan her bir temel olayı 7 dereceli sezgisel ölçek üzerinden göreceli önemlerine göre puanlamaları istenmiş ve değerlendirmeler riskin frekans ve şiddet çarpımıyla hesaplanma prensibiyle yönlendirilmiştir. Uzmanların tamamının bitüm tanker operasyonlarında doğrudan deneyim sahibi olması, verilerin güvenilirliğini ve analiz bulgularının uygulanabilirliğini önemli ölçüde artırmıştır.

Çalışma kapsamında etik ilkelere bağlı kalınarak herhangi bir şirket veya gemi adı belirtilmeden, sektörde yaşanmış bitüm tankeri kazalarına ait raporlar derinlemesine incelenmiş ve özetlenmiştir. Bu analizler, olayların yüzeyde kalan semptomlarından ziyade temel sistemsel eksiklikleri ortaya koyarak kök nedenlere ulaşmayı kolaylaştırmıştır. Böylelikle çalışma yalnızca mevcut riskleri analiz etmekle kalmamış, aynı zamanda daha proaktif bir yaklaşım benimseyerek risk düşürme stratejileri ve kaza önleyici bir yol haritası oluşturulmasına da zemin hazırlamıştır.

Analiz bulguları, operasyonel başarısızlıkların en çok insan faktörü ve organizasyonel yetersizliklerden kaynaklandığını ortaya koymuştur. Özellikle sıcaklık kontrol sistemlerindeki süreksizlik, yalıtım hataları, acil durumlara hazırlıksızlık ve prosedürlerin yetersiz uygulanması öne çıkan zayıf alanlar arasında yer almıştır. Bu doğrultuda; personel eğitimi, bakım planlaması, operasyonel standartların gözden geçirilmesi ve kriz senaryolarının önceden yapılandırılması gibi stratejik öneriler geliştirilmiştir.

Ayrıca, gemi tasarımı, yalıtım verimliliği ve ısıtma sistemlerinin risk üzerindeki etkileri çok boyutlu bir risk matrisi kapsamında değerlendirilmiş; teknik sistemlerin güvenilirliği ile insan kaynaklı faktörlerin bütüncül olarak ele alınması gerektiği vurgulanmıştır. Bu çerçevede sadece mevcut risklerin analiziyle yetinilmemiş, aynı zamanda önleyici bir güvenlik kültürünün oluşturulmasına katkı sağlanması amaçlanmıştır.

Bu çalışmada kullanılan IFFTA yöntemi, klasik yöntemlerin belirsizlik içeren alanlardaki sınırlılıklarını aşarak daha güvenilir ve kapsamlı risk öngörülerini sunmuştur. Özellikle sezgisel bilgi ile nicel analizlerin bir arada sunulması, denizcilik sektöründe sistemsel arıza modellenmesine yeni bir yaklaşım getirmiştir. Bu yönüyle

tez, hem akademik literatüre özgün katkı sađlayan hem de saha uygulamalarına dođrudan yol gsterici nitelikte öncü bir çalıřmadır.

Sonuç olarak, bu çalıřma sadece teknik bir risk deđerlendirmesi sunmakla kalmayıp, aynı zamanda bitüm tanker operasyonlarının daha güvenli, sürdürülebilir ve öngörülebilir bir yapıya kavuřmasına katkı sađlayacak stratejik bir rehber niteliğindedir. Elde edilen sonuçlar; sektör profesyonelleri, gemi iřletmecileri ve karar vericiler için önemli bir referans kaynađı olarak deđerlendirilmektedir.





1. INTRODUCTION

Maritime transportation constitutes the backbone of global trade, accounting for approximately 80% of the world's trade volume and serving as a cornerstone of industrial development (UNCTAD, 2024). In this era where global economies are highly interconnected, seaborne transport enables the shipment of large volumes of cargo in an economical, efficient, and secure manner. Within this framework, tanker vessels represent a significant cargo category by carrying the majority of the world's liquid bulk, and are further classified into sub segments based on the specific nature of the products they transport. Bitumen tankers, in particular, hold a unique position within these segments due to the distinct physical and chemical properties of their cargoes. Bitumen is a substance that requires transportation at elevated temperatures, possesses extremely high viscosity, and carries notable environmental implications—therefore, its carriage necessitates carefully engineered vessel designs and specialized operational procedures.

The primary objective of this study is to systematically analyze the technical, environmental, and organizational challenges encountered in the operational processes of bitumen tanker vessels, to identify associated risks, and to propose practical solutions to mitigate them. Within the scope of the research, a sector-guiding analysis is aimed to be developed through real-life operational incidents, potential scenario-based risk assessments, and field data. In this context, the study will present a practice-oriented framework grounded in hands-on experience from the field, going beyond purely theoretical knowledge. Furthermore, this analysis will adopt an interdisciplinary perspective by bridging multiple domains such as naval architecture, maritime operations management, environmental engineering, and human resources management.

Bitumen stands out as an essential raw material in modern construction and infrastructure projects, primarily used in asphalt production (Eurobitume, 2022). However, the transportation of bitumen must be carried out within a specific temperature range to preserve its physical properties, which introduces significant technical complexities. Due to its requirement for high temperature carriage, several

parameters such as temperature control, insulation, and continuous heating become critical in these operations. Maintaining a stable temperature within the cargo tanks and ensuring the flowability of discharge lines are key factors that directly affect the continuity of the operation.

A failure in the heating system during transportation may lead to the solidification of the cargo, blockage of discharge pipelines, damage to equipment, and operational delays. In particular, regions prone to temperature loss such as cargo pipelines, pumps, and tank bottoms—are especially vulnerable to these risks. Furthermore, temperature imbalances are also of critical importance with respect to vessel stability. Discrepancies in cargo levels can negatively impact ship stability and pose a threat to navigational safety. In addition, environmental conditions such as wind and sea state during the voyage can influence the performance of the thermal control systems.

Environmental impacts also play a prominent role in bitumen transportation. In the event of a spill or leakage, long-term adverse effects may occur on marine ecosystems. Factors such as the spreading behavior of bitumen on water, its density, and its resistance to biodegradation make cleanup efforts in such incidents extremely challenging. Therefore, emergency response procedures and risk mitigation plans are of critical importance in vessel operations. Moreover, a comprehensive understanding of the environmental toxicity of the cargo and proper crew training within this context are essential.

The human factor is likewise an integral component of operational safety. Crew members must be thoroughly trained to understand the characteristics of the cargo, operate relevant systems correctly, and respond effectively to emergencies. Proper management of temperature control processes, discharge procedures, and valve operations can significantly reduce the likelihood of human error. A lack of training, insufficient experience, or procedural deviations may become root causes of systemic failures and lead to serious operational disruptions.

When all these elements are evaluated collectively, it becomes evident that bitumen tanker operations must be approached not only from a technical standpoint but also with careful consideration of environmental, human, and systemic dimensions. This thesis aims to analyze in detail the causes, consequences, and solutions related to the challenges faced in bitumen transportation, with particular emphasis on offering

strategic, practice-oriented recommendations. Furthermore, the study aspires not only to contribute to academic knowledge but also to provide practical guidance for maritime industry personnel and decision-makers.

A review of the existing research in this field reveals that most studies related to bitumen tanker vessels are predominantly focused on design and engineering aspects, while there is a limited number of in-depth analyses addressing operational processes, failures, and risk management. In particular, there is a noticeable lack of comprehensive evaluations concerning operational dynamics, human factors, and environmental risks. This study has been prepared not merely to address a gap in academic knowledge, but with the intention of serving as a practical guide for seafarers, operators, and managers actively working in the maritime industry. The aim is to contribute to the enhancement of current practices, to objectively assess the challenges encountered, and to offer a systematic perspective for operational improvement.

1.1 Purpose of the Thesis

The thesis is not merely a theoretical investigation; rather, it represents an in-depth analysis that integrates field data, real-life operational experiences, and a comprehensive literature review. In this regard, the study aims to serve as a comprehensive resource that can benefit stakeholders within the bitumen tanker transportation sector. The methodologies employed in the research have been designed to yield both objective and practically applicable results. Thus, this thesis not only contributes to academic knowledge but also serves as a guiding reference for real-world maritime operations.

Throughout this study, no specific country or company names are mentioned. In line with ethical principles, the focus is strictly limited to operational processes, technical infrastructure, and associated risks. In doing so, the study provides seafarers and operators active in the sector with the opportunity to manage operational risks more effectively, avoid systemic failures, and foster a stronger safety culture. Ultimately, this thesis seeks to bring to light the dynamics of a niche field, enriched by scientific research methodologies, and to establish itself as a reference guide that contributes to the advancement of sustainable maritime transportation.

1.2 Literature Review

The transportation of bitumen by sea presents unique operational and safety challenges due to the material's thermophysical properties and sensitivity to temperature fluctuations. While general maritime risk assessment has been extensively explored through deterministic models and traditional FTA, there exists a significant gap in the literature specifically addressing the complexities of bitumen logistics. Previous studies have focused largely on crude oil and chemical tanker operations, with limited attention to the intricacies of transporting semi-solid, high-viscosity substances like bitumen.

In recent years, fuzzy logic based approaches have gained prominence in risk modeling, particularly in scenarios marked by high uncertainty and expert reliance. IFS and their integration into FTA have emerged as powerful tools for capturing expert hesitation and partial truth, offering a more realistic representation of system vulnerabilities. However, their application to niche maritime sectors such as bitumen tanker operations remains scarce.

This literature review synthesizes existing research on maritime hazard identification, fuzzy logic applications in safety analysis, and the regulatory frameworks governing bitumen carriage. It highlights the need for an interdisciplinary methodology that incorporates engineering design, human reliability, environmental stressors, and adaptive risk governance to adequately model and mitigate the unique risks associated with bitumen transport.

1.2.1 Description of bitumen

Bitumen is a high-viscosity, dark colored, petroleum derived complex mixture of hydrocarbons that is widely used in modern industrial processes and infrastructure projects. Due to its structural characteristics, bitumen remains solid at lower temperatures and must be heated to specific temperature ranges to become fluid for handling and transportation. Bitumen, although solid at ambient temperatures, is classified under MARPOL as a category that requires careful handling due to its potential to cause marine pollution when discharged in heated or emulsified form. Typically, bitumen remains in a liquid state within the temperature range of 100 °C to 230 °C; outside of this range, it rapidly solidifies and its viscosity increases significantly (Eurobitume, 2013; Asphalt Institute, 2013). These characteristics

introduce technical challenges in the transportation, storage, and processing of bitumen, necessitating the use of specialized equipment.

Furthermore, the physical properties of bitumen have led to the development of various forms tailored for different applications, resulting in both naturally occurring and industrially processed types of bitumen. Consequently, the types of bitumen and their respective production methods have a direct impact on their areas of application and on the conditions required for their transportation.

Bitumen is generally classified into two main categories: natural bitumen and refinery-produced bitumen. Natural bitumen is derived from hydrocarbon deposits that have formed naturally in various regions of the Earth's crust. These deposits occur in different forms, such as rock bitumen and oil sands. Rock bitumen, commonly known as gilsonite, is a high-purity, hard, glossy black substance found in vein-like formations underground. Gilsonite veins typically range in width from 2 to 28 feet and can extend for several kilometers in length and reach depths of up to 1,500 meters (Nciri et al., 2014). Geologically, these veins usually align in a northwest-to-southeast direction and are arranged in parallel patterns.

The extraction of gilsonite is primarily concentrated in the United States particularly in the states of Utah and Colorado as well as in countries such as Iran and Colombia. In industrial applications, gilsonite can be used either in block form or processed into micronized powder. It is especially favored in the paint, ink, construction, and road surfacing industries due to its high purity. Gilsonite is also referred to by various names including natural asphalt, asphaltite, uintaite, and asphaltum, with each name reflecting its usage in different application areas (Nciri et al., 2014).

Another natural source of bitumen is oil sands, which consist of sand deposits with high bitumen content and are also referred to as tar sands or bituminous sands. It is estimated that global bitumen reserves contained within oil sands amount to approximately 100 billion barrels (around 15.9 billion cubic meters). Approximately 70.8% of these reserves are concentrated in the Alberta region of Canada, with the remainder found in countries such as Kazakhstan, Russia, and Venezuela (Bauquis, 1998; Oil and Energy Trends, 2006). The bitumen present in oil sands exists in a solid state and has a more complex composition than conventional heavy crude oil.

To process this raw material, various extraction and thermal techniques must be applied, which in turn result in significant environmental and energy-related costs. Although oil sands are considered a substantial reserve resource for the energy sector, their environmental impact and high production costs place them in a controversial position. Nevertheless, they continue to hold a significant place among alternative sources for meeting global energy demand.

Refinery-produced bitumen is obtained during the final stages of crude oil distillation processes and is often subjected to modification procedures to enhance its mechanical and chemical performance. These modifications lead to the production of various commercially significant types such as cutback bitumen, bitumen emulsions, polymer modified bitumen (PMB), and oxidized bitumen (Read & Whiteoak, 2003).

According to recent market research by the Fortune Business Inside, global demand for refinery-produced bitumen is estimated at approximately 128 million tonnes annually, with projections indicating that it may reach 150 million tonnes by 2029, growing at an average compound annual growth rate (CAGR) of 3.2%.

In response to this growing demand, countries such as China, the United States, Brazil, France, and India have emerged as major global producers of refinery-grade bitumen. Alongside these global players, Türkiye also holds a strategic position in regional bitumen production, primarily through domestic refining operations led by TÜPRAŞ, which contributes significantly to the national supply in Figure 1.1.

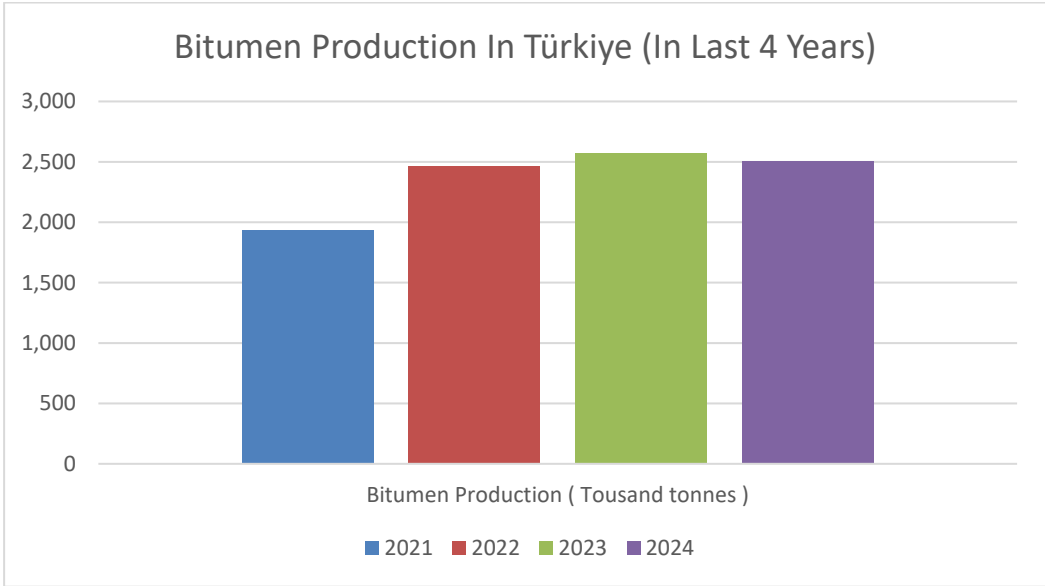


Figure 1.1 : Bitumen production in Türkiye (in thousand tonnes).

Cutback bitumen is a type of bitumen whose viscosity is reduced by the addition of organic solvents (e.g., diesel, naphtha, gas oil, or fuel oil), and it is classified based on its evaporation rate into slow curing, medium curing, and rapid curing types. Bitumen emulsion is produced by dispersing bitumen in water, and it is categorized according to the charge of the emulsifier particles as either cationic or anionic, and by setting time as rapid, medium, or slow setting.

PMB is obtained by incorporating polymer additives to improve the elasticity, durability, and performance of bitumen. The typical polymer content ranges from 1% to 5% by weight, although in some cases it can reach up to 7%. Oxidized bitumen, on the other hand, is produced by blowing hot air through bitumen held over a vacuum bottom, resulting in a product with a harder and more brittle structure (Eurobitume, 2013).

Cutback bitumen is one of the modification types obtained by adding organic solvents to bitumen in order to reduce its viscosity. These solvents include petroleum derivatives such as diesel, naphtha, gas oil, and fuel oil. Due to its ability to remain fluid at lower temperatures, cutback bitumen is particularly favored for spray applications and certain mixing operations. Following application, the solvent evaporates, leaving behind a bitumen residue. Cutback bitumens are classified into three main categories based on their evaporation rates: slow-curing (SC), medium-curing (MC), and rapid curing (RC). The curing rate determines how quickly the applied bitumen sets on the surface and influences its structural performance after application. Slow-curing cutback bitumens are generally used in thicker applications, whereas rapid-curing variants are preferred for thinner layers or situations requiring prompt intervention. The environmental impact of these products must also be carefully considered, particularly in terms of solvent volatility and atmospheric release. Accordingly, proper application techniques and safety measures should be implemented to mitigate potential environmental and health risks.

Bitumen emulsion is another type of modified bitumen, produced by dispersing bitumen in water. During this process, suitable emulsifying agents are used to enable the bitumen to mix with water. Emulsifiers are surface-active agents that allow bitumen droplets to be suspended in water, and they are classified as either cationic or anionic depending on the charge of the particles. Cationic emulsions contain positively charged bitumen particles, while anionic emulsions contain negatively charged ones.

These differences in electrical charge influence how the emulsion interacts with the asphalt surface and determine its adhesion properties. Bitumen emulsions are also classified based on their breaking or setting time, which refers to the rate at which water evaporates and bitumen remains on the surface. This classification includes rapid setting (RS), medium setting (MS), and slow setting (SS) emulsions. Rapid setting emulsions are typically used in surface treatments, whereas slow setting emulsions are preferred for cold mixes and stabilization applications. One of the key advantages of bitumen emulsions is that they can be applied at lower temperatures, thereby providing significant energy savings. Additionally, since no organic solvents are used in their formulation, bitumen emulsions have a lower environmental impact compared to cutback bitumens.

Polymer modified bitumen (PMB) is a type of product obtained by incorporating polymer additives into bitumen to enhance its elasticity, durability, and overall performance. During the modification process, various polymers are blended with the bitumen to improve its mechanical properties. Among the polymers used in PMB production are thermoplastics such as polypropylene, polyethylene, and ethylene-vinyl acetate, as well as natural and synthetic rubbers. These additives increase the bitumen's resistance to cracking, improve its deformation tolerance, and reduce its sensitivity to temperature variations. The polymer content typically ranges from 1% to 5% by weight, although it may reach up to 7% in specialized applications (Eurobitume, 2013).

PMB is particularly preferred in road paving applications, where it enhances durability under heavy traffic loads while also reducing the risk of cracking at low temperatures. The elastic properties of these products provide greater resistance to fatigue and stripping-related deformations. Furthermore, PMB can be enriched with recycled materials. For instance, ground scrap tires or crumb rubber from used tires are commonly employed in the production of polymer modified bitumen, contributing to environmental sustainability. These recycled polymers may constitute between 5% and 20% of the binder's weight, depending on the type of material used and the specific requirements of the application.

1.2.2 Associated details of the bitumen regarding health and environment

Despite the relatively inert nature of bitumen, the environmental and health risks associated with its transportation and handling must be addressed with due diligence.

In particular, when bitumen is transported or processed at high temperatures, it may release hazardous components such as volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), both of which pose risks to human health and the environment. This exposure places personnel working in areas of direct contact with bitumen at heightened health risk. The International Agency for Research on Cancer (IARC) has evaluated occupational exposure to bitumen emissions and, in certain cases, classified them as potentially carcinogenic. For example, exposure to oxidized bitumen and its emissions in roofing applications has been classified as Group 2A "probably carcinogenic to humans." Meanwhile, exposure to straight-run bitumen and its emissions during road paving activities has been classified as Group 2B "possibly carcinogenic to humans." These classifications highlight the necessity of considering the long-term health effects of occupational exposure in bitumen-related operations (IARC, 2011; Loomis et al., 2018).

In a comprehensive two-year dermal carcinogenicity study using C3H/HeNCR1 mice, Clark et al. (2011) investigated the tumor-forming potential of asphalt fume condensates derived from both paving and oxidized roofing bitumen. The results revealed that fume condensates originating from paving bitumen showed no carcinogenic effects on the test animals, while those from Type III oxidized roofing asphalt (BURA) led to varying degrees of skin tumors. The incidence and severity of tumors were significantly higher in animals exposed to lab-generated BURA fumes compared to those exposed to field-matched samples, highlighting the role of generation conditions in toxicity outcomes. The study underlines that the biological impact of asphalt fumes on mammals depends heavily on fume composition, application temperature, and oxidation level of the asphalt, and it demonstrates that real-world exposures may result in substantially lower risks than those produced in artificial laboratory settings.

However, studies conducted by Kriech and Osborn have indicated that the existing data are insufficient to conclusively demonstrate the health effects of bitumen emissions on humans. Although increases have been observed in biological indicators such as DNA damage, sister chromatid exchange, micronucleus formation, and chromosomal abnormalities, these findings do not provide adequate evidence to confirm a direct link to carcinogenesis. This suggests that exposure may cause

heritable genetic damage and poses a potential risk, yet the current body of evidence is not sufficient to warrant a definitive carcinogenic classification.

Due to the environmental and health risks that may arise during transportation, bitumen logistics are strictly regulated under international transport regulations and risk assessment standards. Bitumen products classified under UN 3082 fall within Packing Group III and are defined as substances presenting low to moderate environmental hazards. This classification mandates the application of specific standards, packaging requirements, and spill response protocols during the transportation of bitumen. Transport operators are required to use approved containers to minimize the risk of spillage and must have in place contingency plans and appropriate equipment for rapid response in the event of an incident. In maritime transport specifically, the International Maritime Dangerous Goods (IMDG) Code and guidelines established by the International Maritime Organization (IMO) prescribe dedicated safety standards for vessels carrying bitumen. These standards include criteria such as effective heating and insulation of cargo tanks, leak-proof sealing measures, and the availability of emergency response equipment according to the IBC Code. Numerous studies have emphasized that the environmental impact of transportation activities should not only be assessed during the carriage itself but also evaluated in terms of their post-transport consequences.

In a study conducted, the use of various plant species was investigated to prevent soil contamination in areas affected by bitumen production and refinery operations. The research demonstrated that certain plants, such as North American reed and alfalfa, were highly effective in the remediation and rehabilitation of soils contaminated with bitumen. The root structures of these plants contribute to both the physical and chemical cleaning processes by absorbing hydrocarbons accumulated in the soil, thus offering an effective bioremediation strategy from an environmental sustainability perspective (Muratova et al., 2003). These findings highlight that bitumen transportation and processing activities must be addressed not only through strict transport safety standards but also from a broader environmental standpoint, including the mitigation of potential ecological impacts and the protection of natural ecosystems.

The regulatory framework has been developed with the aim of minimizing risks to both the environment and human health during the transportation, handling, and storage of bitumen products. The Globally Harmonized System of Classification and

Labelling of Chemicals (GHS) mandates the classification and labelling of bitumen and similar products according to their risk levels in international transport. The European Union's CLP (Classification, Labelling and Packaging) Regulation imposes specific classification criteria on bitumen products due to their environmental hazard potential and requires appropriate labelling and safety measures during transport operations. These regulations apply not only to land transportation but also to international maritime operations, and are strictly enforced particularly for bitumen tankers entering EU ports. In port inspections, consistency between shipping documents and physical labels is strictly verified, and in the case of discrepancies, severe administrative sanctions may be imposed. In this context, regular crew training, continuous document updates, and the implementation of sustainable environmental safety measures throughout the transport chain are of critical importance for vessels carrying bitumen (European Commission CLP Regulation).

1.2.3 Transportation methods of the bitumen

Maritime transportation, as one of the largest components of global trade, accounts for approximately 80% of worldwide trade volume as per the Statistica researches in 2024. In comparison, road and rail transport collectively handle around 14% of global trade, while air transport contributes less than 1% to the overall logistics balance. Within maritime transportation, tanker vessels constitute the majority of liquid cargo transport, representing approximately 28% of the global maritime trade volume (UNCTAD, 2024). These vessels are subdivided into specialized segments designed for the carriage of various product groups such as crude oil, chemical products, and liquefied gases. Among these segments, bitumen tankers hold a unique position due to the specific physical and chemical characteristics of the cargo they carry, requiring distinct design, operational, and safety considerations.

Globally, there are approximately 230 bitumen tanker vessels currently in operation, with a combined transport capacity of around 1.543 million tons. This figure accounts for only 0.22% of the total transport capacity of the global tanker fleet, which stands at 679 million tons. Although this proportion may appear relatively small, the specialized equipment and operational procedures required for transporting bitumen a highly specific cargo—significantly enhance the strategic importance of this segment within maritime transportation (Marine Traffic, 2025).

1.3 Specification and Handling of the Bitumen

Bitumen tankers are equipped with advanced heating systems and insulation technologies to ensure that the high viscosity bitumen remains in a liquid state during transport, with temperature continuously maintained within controlled limits. These vessels incorporate specialized engineering solutions designed to enable the safe transport of the product and to ensure efficient discharge at the destination port.

Due to the specific characteristics of the cargo they carry, bitumen tanker vessels are required to maintain certain temperature ranges during transport. In order to keep bitumen in a liquid state, it typically must be maintained within a temperature range of 130 °C to 180 °C. These elevated temperatures reduce the viscosity of the cargo, making it suitable for pumping and transport. To meet these requirements, the cargo tanks of bitumen tankers are equipped with specialized insulation materials and integrated heating systems. The cargo tanks are designed with floating-type structures that are resistant to thermal expansion. This design allows for the controlled release of expansions caused by temperature fluctuations along the tank walls, thereby preventing structural deformation. Such tank configurations are capable of maintaining their structural integrity even under temperature variations of ± 20 °C around the transport range of bitumen.

The insulation materials used around cargo tanks also play a critical role during the transport process. For this purpose, high temperature resistant materials such as ceramic fiber insulation, mineral wool, or rock wool are commonly utilized. These insulation systems help minimize heat loss and enhance energy efficiency by balancing the temperature differential between the tank interior and the external environment, which can reach up to 100 °C on average. The outer surfaces of the insulation materials are typically reinforced with aluminum alloy or stainless steel sheets, with a thickness ranging from 1.5 to 2 mm. Additionally, high-temperature-resistant EPDM gaskets and metal clamping strips are used at the joints to prevent the formation of thermal bridges and to ensure complete sealing with 100% leak-tightness.

In terms of heating systems, coil systems utilizing thermal oil are commonly preferred to maintain the bitumen at a stable transport temperature. These systems operate using thermal oil instead of steam. The primary reason for choosing thermal oil is that water vaporizes at 100 °C, leading to uncontrolled expansion. In contrast, thermal oil systems

can operate stably at temperatures up to 200 °C, require minimal maintenance, and provide precise temperature control with an accuracy of ± 2 °C. These features ensure uniform temperature distribution throughout the vessel during bitumen transport, while also enabling accurate regulation of the cargo's consistency and viscosity.

The discharge of bitumen and similar products transported at high temperatures requires specialized systems. One of the most commonly used systems in this process is steam turbine-driven cargo pumps. In these systems, high-temperature and high-pressure steam generated by the ship's boiler is directed onto the turbine blades, where it is converted into mechanical energy. This energy is then transmitted directly to the pump shaft, enabling the transfer of high viscosity liquid cargo through the pipeline network. One of the primary advantages of steam turbine-driven pumps is their ability to generate significantly higher torque compared to electrically driven alternatives. This high torque capacity plays a critical role, particularly during the initial startup phase when considerable force is required to initiate the movement of highly viscous fluids.

Electric gear pumps used during the cargo discharge operations on bitumen tanker vessels are specifically designed to ensure the stable and safe transfer of high-viscosity fluids. In these systems, screw-type rotary pumps characterized by their positive displacement mechanism enable laminar flow with low shear force, while transporting the fluid in sealed chambers from suction to discharge with consistent volumes. The pump shaft is supported by externally mounted bearings, which balance axial and radial forces and minimize wear. Gear pumps are driven directly by electric motors, with torque transmitted through flexible couplings. This configuration absorbs axial misalignments and vibrations, ensuring reliable and stable operation. Sealing is achieved through a double-acting mechanical seal system combined with a thermosiphon arrangement, which provides effective cooling and lubrication of the seals—thus prolonging the service life of the pump. These systems are capable of operating stably even at high temperatures (up to 250 °C), making them suitable for handling heavy fluids such as bitumen

Another advantage of electric gear pump systems is their modular design, which offers flexibility during maintenance and installation procedures. Most pump components—such as bearing housings, covers, and mechanical seals—can be easily disassembled and replaced on-site, resulting in significant time and labor savings during tanker

operations. Additionally, these pumps feature a self-priming capability, enabling the initiation of flow even when the system is initially filled with air. The pump casing and end covers, which are integrated with the heating system, are supplied with thermal oil to ensure that the bitumen remains fluid within the pump body.

It is emphasized that during the installation of suction and discharge lines, sudden directional changes and narrow cross-sections that may disrupt flow balance should be avoided—this being an engineering consideration that directly affects overall system efficiency. Safety measures such as installing pressure gauges on pump flanges and isolating the pump system before performing leak-tightness tests further enhance operational safety.

Moreover, electric gear pump systems, even when operated with explosion-proof (Ex-proof) electric motors in hazardous atmospheres, offer a more cost-effective and easily controllable alternative compared to steam turbine systems. Through motor control units, pump speed can be adjusted, providing operational flexibility for transferring bitumen with varying viscosity levels. The sealing components are designed to allow leakage at a rate of only a few drops per hour as an indication of proper mechanical seal performance. It is strongly emphasized that dry running of the pump must be strictly avoided, and prior to initial startup, the system should be preheated for at least six hours. Temperature monitoring is conducted via sensors integrated into the heating circuit, and any condensate formed at elevated temperatures is collected and discharged from the system. Overall, electric gear pumps present a reliable alternative to steam turbine systems in modern bitumen tanker operations, offering a compact design, low maintenance requirements, precise viscosity control, and efficient energy integration.

The specific properties of bitumen transported at high temperatures, along with the specialized design requirements of the vessel, create distinct differences between bitumen tankers and other chemical tankers. These differences are also reflected in the classification notations assigned to the vessels. Classification societies define certain standards and requirements regarding the structural integrity, safety equipment, and operational procedures of ships, and they assign different notations based on the type of cargo carried. In chemical tankers, the presence of an inert gas system is mandatory due to the volatility and flammability of the cargo. However, this requirement does not apply to bitumen tankers. According to SOLAS Chapter II-2, Regulation 4, inert gas

systems are compulsory for tankers transporting flammable liquids with a flashpoint below 60 °C. Since the flashpoint of bitumen typically ranges between 130 °C and 140 °C, bitumen cargoes fall outside the scope of this requirement. Consequently, bitumen tankers are exempt from the obligation to be equipped with inert gas systems.

This regulatory distinction alters the technical equipment requirements and maintenance procedures of bitumen tankers when compared to chemical tankers, offering a cost advantage in terms of operational expenditures (SOLAS II-2, Regulation 4).

However, the absence of an inert gas system does not imply flexibility in other safety or design aspects. In bitumen tankers, the control of cargo temperature and the effectiveness of insulation systems must provide a safety level equivalent to that ensured by inert gas systems on chemical tankers. For this reason, components such as thermally expandable cargo tank structures, insulation systems, and heating circuits are subject to specific inspections by classification societies. Moreover, criteria such as the capacity of the heating systems, energy efficiency, and emergency procedures as defined by the classification societies for bitumen tankers are considered critical factors in ensuring safe transport operations.

The classification notation differences for bitumen tanker vessels also have a direct impact on their operational processes. In chemical tankers, the inert gas system prevents the accumulation of flammable gases within the tank atmosphere. In contrast, the absence of such a system in bitumen tankers necessitates that fire risk during transport be managed through alternative parameters. The inherently low volatility and high flashpoint of bitumen (130–140 °C) serve as natural safety features that help minimize fire risk during transportation. Nevertheless, insulation systems, temperature control mechanisms, and emergency equipment must still comply with applicable standards. These elements play a critical role in ensuring the operational safety of bitumen tankers and contribute to the diversity of engineering solutions required in vessel design.

The transportation of bitumen and its derivatives is carried out using various methods depending on factors such as the physical properties of the product, its intended application, and the transport distance. Primarily used in the construction and road paving industries, bitumen is a highly viscous material that requires strict temperature

control, necessitating careful logistical planning and specialized equipment during transportation. Bitumen transport is generally performed through four main methods: road, rail, pipeline, and maritime transport. Each of these methods presents its own advantages and limitations, and the choice among them depends on criteria such as transport distance, volume of cargo, and the suitability of existing logistics infrastructure.

Road transport is the most commonly used method, particularly for short-distance deliveries and situations where direct access to construction sites is required. These shipments are carried out using heated tanker trucks (bitutainers), typically with a capacity ranging between 10 and 30 tons. The trucks are equipped with insulation and heating systems to maintain the cargo at a constant temperature between 140 °C and 160 °C during transit. While road transport offers advantages in terms of flexibility and accessibility, it is generally not preferred for long distances due to its higher cost, traffic restrictions, and environmental impact. According to Eurobitume's 2022 data, road transport accounts for approximately 60% of the total bitumen volume transported in Western European countries (Eurobitume, *Annual Bitumen Use Report*, 2022).

Rail transport is another preferred method, particularly for medium-distance routes between refineries and urban centers. Railcars used for transporting bitumen are equipped with specialized heating and insulation systems. However, due to longer transit times and infrastructure limitations in rail transport, heat loss can become more pronounced—especially in colder climate regions where this risk is significantly higher. According to data from the U.S. Energy Information Administration (EIA), approximately 8% of all asphalt and bitumen products transported in North America in 2021 were moved by rail, while 6% were transported via pipeline. The remainder was shipped by road and maritime transport (U.S. Energy Information Administration, *Petroleum and Other Liquids – Asphalt and Road Oil Movements*, 2021).

Maritime transport stands out as the most suitable and cost-effective method for international and intercontinental bitumen shipments. Particularly for long-distance transportation of large volumes, seaborne logistics play a strategic role in terms of energy efficiency and bulk handling capacity. For this purpose, bitumen is transported using specially designed asphalt/bitumen tanker vessels. These ships typically range in capacity from 3,000 DWT to 40,000 DWT and are equipped with fully insulated

cargo tanks and advanced heating systems. For instance, IMO Type 2-certified asphalt tankers are engineered to transport bitumen at temperatures of up to 250 °C in the IBC Code.

Maritime transport is gaining increasing importance, especially for shipments to markets in the Middle East, Southeast Asia, and Africa. According to the *Global Bitumen Market Report 2023*, approximately 15% to 20% of global bitumen transport is carried out by sea (IMARC Group, *Bitumen Market: Global Industry Trends, Share, Size, Growth, Opportunity and Forecast 2024–2032*). Although this percentage may appear modest in terms of total volume, maritime transport offers the highest efficiency for long-distance and large-scale shipments. For example, a bitumen tanker carrying 10,000 tons of cargo is equivalent to hundreds of truckloads by road, resulting in significant advantages in both cost and carbon emissions.

Maritime transport also holds an indispensable position in the export of refinery-origin bitumen products to developing countries. More than 90% of bitumen shipments from India to East Africa, from Turkey to North Africa, and from China to Southeast Asia are carried out via sea. Likewise, nearly all bitumen exports from Turkey's ports of Ceyhan and İzmit are transported by maritime means (Turkish Statistical Institute [TÜİK], *Crude Oil and Petroleum Products Import/Export Data, 2023*). This underscores the strategic importance of maritime transport specifically in the context of bitumen logistics.

Each transport method used for bitumen presents its own unique challenges. While road transport offers flexibility, it has limited carrying capacity and becomes cost-inefficient over long distances. Rail transport is hindered by infrastructure constraints and the risk of heat loss, whereas pipeline transport is restricted to fixed routes and lacks flexibility. In contrast, maritime transport allows for the shipment of large volumes and provides advantages in terms of energy efficiency and cost-effectiveness. However, maritime transport also presents operational challenges of its own. Key factors that determine the efficiency of this method include maintaining temperature stability over long distances, ensuring vessel stability, and managing environmental risks.

The class notations of bitumen tanker vessels include specific technical and safety requirements that differ from those of standard chemical tankers. While chemical

tankers are typically classified under IMO Types 1, 2, and 3, bitumen tankers are generally evaluated in a manner more closely aligned with Type 2 or Type 3 chemical tanker notations. However, due to the high volatility and flammability of the hazardous chemicals carried by chemical tankers, equipment such as inert gas systems, explosion-proof components, and specific tank coating requirements are mandatory. In contrast, these features differ in bitumen tankers.

Because bitumen has low volatility and a high flash point, inert gas systems are not required on these vessels. Instead, tank coatings are usually limited to materials that can withstand high temperatures, such as heat-resistant steels or ceramic-based linings. While chemical tankers often require tank coatings made of epoxy or stainless steel to resist acids or alkalis, bitumen tankers do not face the same chemical resistance demands. Instead, thermal durability is the primary concern.

As a result, class notations for bitumen tankers specifically include the designation "Asphalt/Bitumen Carrier," distinguishing these vessels from chemical tankers in terms of both cargo type and operational requirements.

The class notation of a representative bitumen tanker clearly outlines the vessel's technical specifications and safety standards as "A1 Tanker for asphalt/bitumen and oil products with flashpoint above 60°C BIS BWM(T) CCO COAT-PSPC(V; B) E0 ECA(SO_x-A) ESP HL(1.3) Hot(250 °C) NAUT(OC) Recyclable TMON VCS(1, B)". This notation indicates that the vessel is authorized to carry asphalt/bitumen and petroleum products with a flashpoint above 60 °C. The symbol BIS refers to the vessel's compliance with ballast water management standards, while BWM(T) denotes technical compliance with the Ballast Water Management Convention. CCO indicates that the vessel holds a class certificate of compliance. COAT-PSPC(V; B) refers to protective coating standards in accordance with the Performance Standard for Protective Coatings (PSPC) for void spaces and ballast tanks. E0 designates the ship's automation level, enabling unattended machinery operation. ECA(SO_x-A) signifies compliance with Sulphur Oxide (SO_x) emission control regulations within Emission Control Areas. ESP reflects compliance with Enhanced Survey Program requirements for structural integrity, and HL(1.3) denotes the allowable cargo density per tank. The notation "Hot(250 °C)" specifies that the cargo tanks are designed to maintain operating temperatures up to 250 °C. NAUT(OC) indicates the vessel is equipped with advanced navigation and operational control systems. Recyclable certifies that the ship

has been constructed with recyclability in mind. Lastly, TMON and VCS(1, B) refer to the tank monitoring and vapor control systems, indicating compliance with specific technical standards for cargo safety and vapor emission management.

The fundamental differences between chemical tanker and bitumen tanker class notations stem from the distinct characteristics of the products they are designed to transport. For example, a typical chemical tanker notation may read: "1A1 Tanker for chemicals and oil AP(1) BIS CCO E0 ESP HL(1.54) Inert TMON VCS(1)". In this notation, AP(1) denotes explosion-proof zones and systems, while Inert signifies the mandatory presence of an inert gas system. The HL(1.54) symbol indicates the vessel's capacity to carry higher-density chemical cargoes. Tank coating requirements and cargo safety standards in such vessels are optimized to address the risk of chemical reactions and corrosive damage. In contrast, bitumen tankers are not subject to these chemical resistance and inert gas requirements. Instead, the focus shifts to high-temperature resistance, integrated heating systems, and the vessel's capacity for temperature-controlled operations. These distinctions establish bitumen tankers as possessing an operational profile independent from that of chemical tankers, leading to class notations that emphasize asphalt/bitumen-specific criteria and capabilities.

Through this thesis study, an in-depth risk assessment has been conducted to investigate potential failures in the operational processes of bitumen tanker vessels, with a focus on identifying root causes. The selected methodology, Intuitionistic Fuzzy Fault Tree Analysis (IFFTA), has been employed as a robust analytical tool due to its effectiveness in both systematic fault detection and modeling under uncertainty. The primary objective of this method is to evaluate failure probabilities with greater precision in environments and processes characterized by ambiguity. Using this analytical approach, the risks associated with operational stages—including loading, laden voyage, discharging, and their disconnected sub-phases—have been structured through top events, intermediate events, and basic events. The development of a detailed fault tree enabled each component within the operational chain of a bitumen tanker vessel to be examined individually, thereby facilitating the identification of root causes underlying potential failures.

The structured fault tree was modeled in accordance with the principles of intuitionistic fuzzy logic and evaluated based on expert opinions gathered through interviews with professionals in the field. These expert insights were statistically analyzed at regular

intervals and prioritized accordingly. By ranking the most critical risk factors, the study identified the fundamental issues that threaten both operational efficiency and safety. As a result, this thesis not only presents a comprehensive risk assessment but also provides tangible insights that can inform industry practices. The analysis encompasses not only technical equipment failures but also human errors, environmental conditions, and organizational deficiencies, offering a holistic perspective on risk within bitumen tanker operations.

In this thesis, a comprehensive risk assessment was conducted to investigate potential failures within the operational processes of bitumen tanker vessels, with a focus on identifying root causes. The selected methodology, IFFTA, was chosen as a powerful analytical tool for both systematic fault identification and effective modeling under conditions of uncertainty. The primary aim of this method is to evaluate failure probabilities with enhanced precision in environments and processes characterized by ambiguity.

Using this analytical framework, risks within operational phases—including loading, laden voyage, discharging, and non-continuous subprocesses—were structured through top events, intermediate events, and basic events. The detailed fault tree constructed in this context enabled each element of the operational chain in bitumen tanker operations to be examined individually, thereby facilitating the tracing of root causes behind potential failures.

This structured fault tree was modeled in accordance with the principles of intuitionistic fuzzy logic and evaluated based on expert interviews conducted with professionals in the field. The expert opinions were statistically analyzed at regular intervals and prioritized, enabling the identification of the most critical risk factors. As a result, the fundamental issues threatening operational efficiency and safety were determined. Consequently, this thesis does not merely present a risk assessment; it also delivers concrete insights that can inform and guide industry practices. The analysis encompasses not only technical equipment failures but also human errors, environmental factors, and organizational deficiencies. Moreover, the findings include interpretations of the results, an exploration of their actual and potential implications, and proactive mitigation strategies to address such potential sources of hazard.

2. METHODOLOGY

In this study, the IFFTA method was employed to model the systemic risks encountered during the discharge operations of bitumen tanker vessels. IFFTA is an extended form of the classical fault tree analysis technique, incorporating fuzzy logic and intuitionistic evaluation capabilities (Kumar & Singh, 2019). This method enables the systematic inclusion of uncertainties and indecisiveness related to expert judgments into the model, allowing for a more in-depth analysis in areas where conventional methods remain limited.

As part of the analysis process, a fault tree was initially constructed based on interviews conducted with experts possessing operational experience in bitumen tanker vessels. The top event of this tree was defined as an operational failure, and the contributing intermediate events and basic events were modeled in a logical structure (Zhang et al., 2020). The structure of the fault tree encompasses systemic, environmental, and human-related components corresponding to each phase of the operation—including loading, navigation, discharging, and the process-independent stages associated with them.

The expert panel was composed of individuals from diverse disciplines such as ship management, engineering, and classification inspection, each possessing over ten years of professional experience. The knowledge and experience level of each expert was evaluated using a statistical weighting factor (WF), enabling the expert opinions to be analyzed not only in a qualitative framework but also through a quantitative perspective (Wang et al., 2015).

The assessments related to these basic events were modeled using Intuitionistic Fuzzy Numbers (IFNs). These numbers allowed experts to express their judgments under uncertainty, incorporating the degree of "hesitation" into the decision-making process. Expert opinions were encoded through a seven-level linguistic scale ranging from "very low" to "very high," and these linguistic expressions were subsequently quantified through statistical transformation (Liu & Wang, 2022).

The collected data were analyzed using MATLAB and Excel platforms. By applying α -cut and membership–hesitation measurements, the risk weights of each basic event were calculated. As a result of these analyses, the events contributing most significantly to the system were identified, and the most critical fault paths were determined through Minimal Cut Sets (MCS). Furthermore, the Fussell-Vesely Importance Measure (FVIM) calculations were used to rank the relative significance of each event within the overall system, thereby quantifying their proportional impact on the operational failure processes identified as the top event in bitumen tanker operations (Xie et al., 2017).

Through this methodology, low-probability but high-impact risks were also made visible, allowing the analysis to go beyond traditional deterministic models and providing decision-makers with more realistic and applicable recommendations. The comprehensive analytical capability offered by this method presents a unique and effective approach, particularly in high-risk and data-scarce domains such as bitumen tanker operations.

During the methodological evaluation, experts were specifically requested to focus on risk assessment methods while providing survey-based responses. They were asked to assess risks based on the product of frequency and severity levels as multipliers. Considering the formula of the risk, intuitive judgment-based evaluations were collected and subsequently processed using the aforementioned methods to obtain statistically calculated results in a structured manner.

2.1 Fault Tree Analysis

Fault Tree Analysis (FTA) is a logic-based analytical method developed to systematically investigate the causes of undesired outcomes that may occur within systems. The method was first introduced in 1961 by Bell Telephone Laboratories as part of the Minuteman missile control system project for the United States Air Force. It later gained widespread attention in the engineering community, particularly following a safety symposium held in 1965 (Lee et al., 2019).

FTA examines the highest-level event in a system that may result in failure—referred to as the top event—and graphically links the subordinate component failures that could cause it. This logical diagram is known as the fault tree. In FTA, events are

modeled as *basic events*, and their combinations are represented using logical gates such as *AND* and *OR*. The *AND* gate indicates that all input events must occur simultaneously for the output event to happen. Typical FTA applications generally follow these four steps:

Definition of the system and the boundaries of the analysis

Construction of the fault tree structure

Qualitative evaluation of potential failure paths (Minimal Cut Sets)

Quantitative calculation of fault probabilities

During the qualitative evaluation process, the smallest possible combinations of causes that may lead to system failure are identified. These combinations are referred to as *minimal cut sets*, and their analysis reveals the weak links within the system. In such analyses, Boolean algebra is typically used to compute the logical relationships between failures.

In the quantitative evaluation phase, the probability of system failure within a specified time period is calculated based on statistical data. Under the assumption of independent events, multiplication is applied for *AND* gates, while addition is used for *OR* gates.

For example:

For an AND gate:

$$P_{Top}=P(A)\cdot P(B) \quad (2.1)$$

$$P_{Top}=P(A)\cdot P(B)$$

For an OR gate:

$$P_{Top}=P(A)+P(B)-P(A)\cdot P(B) \quad (2.2)$$

FTA is widely used in safety-critical domains such as nuclear power plants, chemical process systems, aviation, and naval architecture. Its applicability to complex systems has significantly increased, particularly with the development of numerical analysis software after the 1970s. Tools such as the “Fault Tree Synthesis” method developed by Lapp and Powers, and the “DRAFT” software designed by Fussell, have enabled the automation of this technique.

The primary advantage of FTA lies in its ability to identify all potential failure paths within a system both visually and quantitatively, thereby supporting the development of preventive engineering measures. Moreover, its integrated approach to analyzing the impact of human error, environmental factors, and component failures within a unified framework has made it a valuable tool for ensuring overall system safety.

2.1.1 Representation of logic gates and calculation of their probabilities

In FTA, the underlying causes of undesired top-level events within a system are modeled using logical relationships. These relationships are typically established through logic gates such as *AND* and *OR*. Each gate determines whether an output event will occur based on the combination of a certain number of input events. This structure allows the system's failure behavior to be evaluated both visually and quantitatively.

2.1.1.1 Probability calculation for the AND Gate

An AND gate indicates that the output event will occur only if all the connected input events happen simultaneously. If the events E_1, E_2, \dots, E_n are mutually independent, and the probabilities of their occurrences are $P(E_1), P(E_2), \dots, P(E_n)$ respectively, then the output probability of the AND gate is calculated as follows:

$$P_{AND} = P(E_1) \times P(E_2) \times \dots \times P(E_n) \quad (2.3)$$

This formula is valid under the assumption of statistical independence between the events. For example, in a bitumen tanker, if both the heating system and the agitator fail simultaneously during discharge, serious consequences such as freezing and blockage in the pipeline may occur. Such combined failures can be effectively modeled using an AND gate.

2.1.1.2 Probability calculation for the OR Gate

An OR gate indicates that the output event occurs if any one of the connected input events takes place. Under the assumption that the events are independent, the probability is calculated as follows:

$$P_{OR} = 1 - (1 - P(E_1)) \times (1 - P(E_2)) \times \dots \times (1 - P(E_n)) \quad (2.4)$$

If the probability of occurrence for each individual event is small (i.e., the events are rare), the formula can be approximated and simplified as follows:

$$P_{OR} \approx P(E_1) + P(E_2) + \dots + P(E_n) \quad (2.5)$$

This approximation offers a practical solution, particularly in systems that involve a large number of potential failure components with low individual probabilities. For instance, during the discharge process, independent failures in various valves and sensors may each have the potential to contribute to an overall system failure.

In a fault tree, each event is represented by a symbol and a descriptor. Events are categorized into types such as basic events, intermediate events, and undeveloped events. The top event is typically denoted by the letter T , and its probability is calculated upward through the logical combinations of events at the lowest level of the tree. This structure allows for a quantitative analysis of the overall system risk level and helps identify priority areas that require corrective action.



3. CASE STUDY

In this section, the risk profile of cargo operations conducted on bitumen tanker vessels is evaluated using IFFTA. The case scenario addresses a comprehensive process encompassing loading, voyage, and discharging operations, and prioritizes risks based on 67 systematically identified BEs.

3.1 General Structure of the Fault Tree

The developed fault tree is structured around four main categories of *Intermediate Events (IEs)*:

Process Independent Failures

Failures During Voyage

Loading Operation Failures

Discharging Operation Failures

Through this structure, the analysis provides a dynamic assessment that spans the entire cargo process, rather than focusing on a specific operational moment. A total of 67 Basic Events (BEs) have been modeled as factors threatening the overall system safety, categorized under the four Intermediate Event (IE) groups mentioned above. For each basic failure, expert evaluations were used to calculate the Critical Failure Possibility (CFP), Failure Probability (FP), Fuzzy Importance Value (FVIM), and Minimal Cut Set (MCS) probabilities.

3.2 Definition and Classification of Basic Events

Each Basic Event (BE) represents a specific defect, failure mechanism, or systemic vulnerability that may arise during the operation. For example:

BE1: Tank Radar Failure and Overfill Alarm Failure

BE3: Failure due to Different Cargo Type

BE11: Cargo Line Wear

BE25: Undrained Cargo Line

BE38: Low Personnel Competence

BE50: Cargo Handling Errors

BE67: Inadequate Operator Performance

All of these basic events encompass technical, environmental, and human-related factors that may have a direct impact on operational safety.

3.3 Fuzzy Scale Construction and Conversation

As previously mentioned, during the expert consultation phase, participants were encouraged to freely share their opinions regarding the constructed fault tree. To evaluate the qualifications and effectiveness of these experts, a weighting score was calculated based on multiple criteria, including their professional competence, years of sea service, shore based operational experience, and educational background. These parameters and their assigned scores are presented in Table 3.1.

Table 3.1 : Anonymous consulted expert and their weights.

No of experts	Professional position	Sea service time (year)	Shore service time (year)	Educational level	Weighting score $ws(E_u)$	Weighting factor $w(E)$
1	Deck Superintendent	≥ 16	6-10	Bachelor	11	0.09
2	Operational Manager	≥ 16	≥ 26	Bachelor	15	0.12
3	HSEQ Manager	6-10	≤ 5	MSC	13	0.10
4	Master	11-15	≤ 5	Bachelor	13	0.10
5	Academician	< 3	11 - 15	PhD	12	0.09
6	Academician	3-5	16 - 25	PhD	14	0.11
7	Master	11-15	≤ 5	MSC	14	0.11
8	Chief Officer	6-10	≤ 5	Bachelor	11	0.09
9	Chief Officer	≤ 3	6 - 10	Bachelor	10	0.08
10	Chief Officer	3-5	11-15	PhD	14	0.11

In line with Miller's cognitive theory (1956), which states that the human brain can process approximately seven pieces of information at once, with a margin of plus or minus two, the number of linguistic terms used in the evaluation process was set between five and nine. Accordingly, a seven point fuzzy linguistic scale was adopted, as illustrated in Figure 4.1. To translate qualitative expert judgments into numerical values suitable for fuzzy logic analysis, the approximation method proposed by Chen and Hwang (1992) was employed. This method utilizes a standardized set of linguistic terms—Very Low (VL), Low (L), Mildly Low (ML), Medium (M), Mildly High (MH), High (H), and Very High (HV)—as shown in Table 3.2. Each linguistic term was then converted into its corresponding fuzzy number and subsequently into trapezoidal fuzzy numbers to facilitate systematic analysis.

Table 3.2 : IFNs and corresponding linguistic expressions.

Linguistic expression	IFNs
Very Low (VL)	(0,0.05,0.1; 0,0.05,0.1)
Low (L)	(0.07,0.13,0.19; 0.06,0.13,0.20)
Mildly Low (ML)	(0.17,0.27,0.37; 0.16,0.27,0.38)
Medium (M)	(0.35,0.50,0.65; 0.33,0.50,0.67)
Mildly High (MH)	(0.63,0.73,0.83; 0.62,0.73,0.84)
High (H)	(0.81,0.87,0.93; 0.80,0.87,0.94)
Very High (VH)	(0.90,0.95,1.00; 0.90,0.95,1.00)

All calculations were individually completed for each of the 67 Basic Events (BEs), which were identified and obtained through step by step analysis. As an illustrative example within this thesis, BE49 *Failure in Operational Planning*, which resulted in one of the highest probability values, was selected for detailed examination in the defuzzification process. The stepwise evaluation of this BE is presented below through Tables 3.3, 3.4 , 3.5 , 3.6 , 3.7.

Table 3.3 : $\tilde{R}_u = (a_u, b_u, c_u, a'_u, b'_u, c'_u)$ experts' judgement for BE49.

Experts	Experts' Judgement					
	a_u	b_u	c_u	a'_u	b'_u	c'_u
E1	0.90	0.95	1.00	0.90	0.95	1.00
E2	0.81	0.87	0.93	0.80	0.87	0.94
E3	0.35	0.50	0.65	0.33	0.50	0.67
E4	0.81	0.87	0.93	0.80	0.87	0.94
E5	0.81	0.87	0.93	0.80	0.87	0.94
E6	0.90	0.95	1.00	0.90	0.95	1.00
E7	0.81	0.87	0.93	0.80	0.87	0.94
E8	0.63	0.73	0.83	0.62	0.73	0.84
E9	0.81	0.87	0.93	0.80	0.87	0.94
E10	0.63	0.73	0.83	0.62	0.73	0.84

Table 3.4 : Expectancy evaluation values of experts for BE49.

$EV(\tilde{R})$	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10
		0.95	0.87	0.50	0.87	0.87	0.95	0.87	0.73	0.87

Table 3.5 : Similarity S_{uv} matrix of experts' opinion for BE49.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
S1	1.000	0.916	0.526	0.916	0.916	1.000	0.916	0.768	0.916	0.768
S2	0.916	1.000	0.575	1.000	1.000	0.916	1.000	0.839	1.000	0.839
S3	0.526	0.575	1.000	0.575	0.575	0.526	0.575	0.685	0.575	0.685
S4	0.916	1.000	0.575	1.000	1.000	0.916	1.000	0.839	1.000	0.839
S5	0.916	1.000	0.575	1.000	1.000	0.916	1.000	0.839	1.000	0.839
S6	1.000	0.916	0.526	0.916	0.916	1.000	0.916	0.768	0.916	0.768
S7	0.916	1.000	0.575	1.000	1.000	0.916	1.000	0.839	1.000	0.839
S8	0.768	0.839	0.685	0.839	0.839	0.768	0.839	1.000	0.839	1.000
S9	0.916	1.000	0.575	1.000	1.000	0.916	1.000	0.839	1.000	0.839
S10	0.768	0.839	0.685	0.839	0.839	0.768	0.839	1.000	0.839	1.000

Table 3.6 : Average agreement $AA(E_u)$ relative agreement $RAD(E_u)$ degrees for BE49.

Average agreement degree $AA(E_u)$		Relative agreement degree $RAD(E_u)$	
E1	0.8491	E1	0.1008
E2	0.8983	E2	0.1066
E3	0.5885	E3	0.0698
E4	0.8983	E4	0.1066
E5	0.8983	E5	0.1066
E6	0.8491	E6	0.1008
E7	0.8983	E7	0.1066
E8	0.8241	E8	0.0978
E9	0.8983	E9	0.1066
E10	0.8241	E10	0.0978

Table 3.7 : Aggregation of experts' opinions on BE49.

Aggregation on BE49					
0.753	0.826	0.900	0.744	0.826	0.909

3.4 Evaluation Methodology and Calculation Process

Expert evaluations were collected using a 7 level relative intuitionistic scale, and the CFP value was calculated for each BE. For example:

The highest CFP value was found for BE49 (0.8266), while the lowest value was observed for BE5 (0.1032). According to the FP analysis, events such as BE1 (0.0369) and BE49 (0.0429) have a higher probability of failure.

Based on the importance ranking derived from FVIM values, BE1 (0.0964) and BE49 (0.112) were identified among the highest priority failure types.

The calculations revealed that values such as FVIM and FP exhibited a parallel trend, with events showing high CFP values generally also possessing high FP scores. This indicates that the critical weak points in the system are prioritized not only in terms of probability but also in terms of their potential impact.

According to the analysis results, the primary factors posing high risk during cargo operations are as follows:

BE1 Tank Radar & Overfill Alarm Failure : Critical loading errors occur due to insufficient system monitoring.

BE49 Failure in Operational Planning : Organizational deficiencies lead to failures during cargo discharge operations.

BE67 Inadequate Operator Performance : The human factor has a direct impact on operational safety.

Additionally, events such as BE38 Low Personnel Competence, BE25 Undrained Cargo Line, and BE50 Cargo Handling Errors identified as critical in terms of both FP and FVIM.

3.5 Review of Case Study

In this study, operational failures that may occur during the discharge operations of bitumen tankers were evaluated using the IFFTA method. Due to the lack of reliable statistical datasets specific to this domain in the literature, expert opinions were utilized for modeling the basic events, and the obtained qualitative assessments were expressed in the form of fuzzy probabilities. These fuzzy values were then defuzzified and used to calculate the overall probability of system failure.

The occurrence probability of the operational failure top event, as identified through the analysis, was interpreted in conjunction with the detection of weak links within the system. MCS were determined, and the reduction in the top event probability resulting from the elimination of any of these sets was calculated.

The findings obtained demonstrate the value of the IFFTA approach not only on a technical level, but also from economic and operational perspectives. It has been observed that, particularly in cases where classical FTA methods fall short due to data scarcity, fuzzy logic based analyses provide reliable and applicable results.

The applied method not only analyzed the current state but also clearly revealed the effects and contribution levels of the basic events that influence the risk of the top event's occurrence. This enables the identification and prevention of risks inherent in the nature of the cargo handling process on bitumen tanker vessels before such risks actually materialize. Consequently, the findings support the development of strategic measures in the context of ship management and risk control, such as implementing preventive training programs, expanding operational procedures, and prioritizing critical points based on operational risk maps.

3.5.1 Explanation of the fault tree structure

The fault tree model developed within the scope of this thesis has been designed to systematically evaluate all potential risks that may arise during discharge operations on bitumen tanker vessels. As shown in Figure 3.1, the top level event of the fault tree referred to as the *Top Event*, namely "Failure of the Discharge Operation" is broken down into subcomponents through four main *Intermediate Events*. This structure logically integrates failures and error types that may occur during loading, navigation, discharging, and process independent phases.

The fault tree is supported by a total of 67 Basic Events (BEs), each modeled to represent a critical risk factor within its corresponding subprocess. The four main Intermediate Events are structured as follows:

3.5.1.1 Process independent failures

This category includes failures of a typically structural or systematic nature that may affect overall system integrity, regardless of the specific phase of the operation.

Example Basic Events:

System shutdown due to loss of excessive thermal oil, line leakage due to improper gasket, explosion risk due to sparking, lack of maintenance procedures, non compliance with the PMS.

3.5.1.2 During loading operation

Risks and failure types that may occur during the loading process are grouped under this category. During the cargo intake phase of the tanker vessel, equipment malfunctions, connection weaknesses, or procedural deviations may result in a failed loading operation.

Example Basic Events:

Operation with a deteriorated hose, tank pressure build up, imbalanced cargo loading temperature stratification, cargo handling errors.

3.5.1.3 During voyage

This category includes events that may occur during navigation due to the vessel's movement, environmental conditions, or uncontrolled variations in tank parameters.

Example Basic Events:

Insufficient isolation, inadequate maintenance planning, lack of thermal oil.

3.5.1.4 During discharging operation

Failures that may occur during the discharge phase are generally related to heating continuity, pipeline fluidity, and pump performance. This section is considered the most critical part of the analysis.

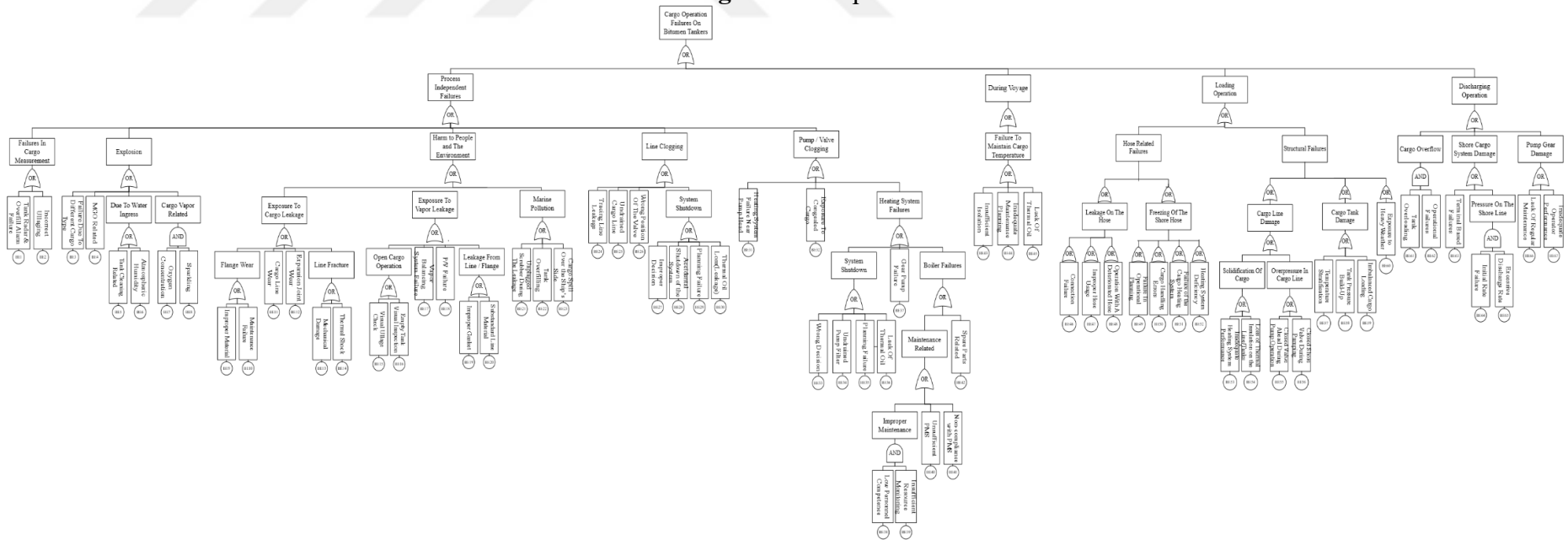
Example Basic Events:

Tank overloading, operational failures, terminal based failures, initial rate failure, excessive discharge rates, lack of regular maintenance, inadequate operator performance.

The BE's under each IE are connected using and/or logic gates, illustrating how events may combine either sequentially or alternatively. This structure clearly models which component level failures may trigger the TE. Furthermore, the entire structure was evaluated using an intuitionistic fuzzy approach, through which CFP values were calculated and risk priorities were ranked accordingly.

Through this modeling approach, risks specific to each phase of bitumen tanker operations were analyzed at both micro and macro levels, enabling the evaluation of technical and organizational factors within an integrated risk framework.

Figure 3.1 : Ope



rational fault tree in bitumen tanker operations.

Table 3.8 : BE's of the fault tree.

BEs	Definition	BEs	Definition
BE1	Tank Radar Failure And Overfill	BE35	Planning Failure
BE2	Incorrect Ullaging	BE36	Lack Of Thermal Oil
BE3	Failure Due To Different Cargo Type	BE37	Gear Pump Failure
BE4	MGO Contamination	BE38	Low Personnel Competence
BE5	Tank Cleaning Related	BE39	Insufficient Resource Monitoring
BE6	Atmospheric Humidity	BE40	Unsufficient PMS
BE7	Oxygen Concentration	BE41	Non compliance with PMS
BE8	Sparkling	BE42	Spare Parts Related
BE9	Improper Material	BE43	Insufficient Isolation
BE10	Maintenance Failure	BE44	Inadequate Maintenance Planning
BE11	Cargo Line Wear	BE45	Lack Of Thermal Oil
BE12	Expansion Joint Wear	BE46	Connection Failure
BE13	Mechanical Damage	BE47	Improper Hose Usage
BE14	Thermal Shock	BE48	Operation With A Deteriorated Hose
BE15	Visual Ullage Check	BE49	Failure In Operational Planning
BE16	Empty Tank Visual Inspection	BE50	Cargo Handling Erros
BE17	Vapor Balancing System Failure	BE51	Failure of the Cargo Heating System
BE18	P/V Failure	BE52	Heating System Deficiency
BE19	Improper Gasket	BE53	Inadequate Heating System Performance
BE20	Substandard Line Material	BE54	Loss of Thermal Insulation on the Line/Tanks
BE21	Unplugged Scrubber During The Leakage	BE55	Closed Valve Ahead During Pump Operation
BE22	Tank Overfilling	BE56	Closed Shore Valve During Pumping
BE23	Cargo Spill Over The Ship's Side	BE57	Temperature Stratification
BE24	Tracing Line Leakage	BE58	Tank Pressure Build Up
BE25	Undrained Cargo Line	BE59	Imbalanced Cargo Loading
BE26	Wrong Position Of The Valve	BE60	Exposure To Heavy Weather
BE27	Improper Decision	BE61	Tank Overloading
BE28	Accidental Shutdown of the System	BE62	Operational Failures
BE29	Planning Failure	BE63	Terminal Based Failures
BE30	Thermal Oil Loss(Leakage)	BE64	Initial Rate Failure
BE31	Heating System Failure Near Pump Head	BE65	Excessive Discharge Rate
BE32	Exposure to Congealed Cargo	BE66	Lack Of Regular Maintenance
BE33	Wrong Decision	BE67	Inadequate Operator Performance
BE34	Undrained Pump Filter		

In the analysis conducted within the scope of this thesis, potential failures that may occur during the cargo operations of bitumen tankers were structured using the IFFTA approach. The constructed fault tree begins with the TE, representing operational failure, and is divided into four main IE categories contributing to this outcome. This structure is systematically modeled based on key operational processes such as loading, voyage, and discharging, along with process independent factors that are common across all phases.

3.5.1.5 Top event (TE)

The TE, defined under the heading "Failure of Cargo Operations," is based on the premise that any failure occurring during the loading, voyage, or discharging phases may lead to overall operational failure. This primary event is further analyzed by dividing it into four main IE groups:

3.5.1.6 IE1 – Process independent failures

This category includes failures that are not directly linked to a specific operational phase (loading, voyage, discharging), but instead arise from design deficiencies, inadequate maintenance, environmental conditions, and organizational weaknesses. BEs ranging from BE1 to BE42 fall under this group:

BE1: Overfilling may occur due to failure of the tank radar system.

BE2: Loading without accurate cargo level detection leads to ullage errors.

BE3: Accidental introduction of a different cargo type creates a contamination risk.

BE4: Mixing with MGO (Marine Gas Oil) may deteriorate bitumen quality.

BE5: Inadequate tank cleaning increases the risk of residue and contamination.

BE6: High atmospheric humidity during loading and voyage affects system performance.

BE7: Elevated oxygen levels inside the tank may create a flammable atmosphere.

BE8: Spark generation, especially during discharging, can cause a fire hazard.

BE9: Use of improper pipes, gaskets, or fittings may result in failure.

BE10: Lack of scheduled maintenance may lead to equipment malfunction.

BE11: Prolonged use causes erosion in the cargo line.

BE12: Wear in expansion joints may result in leakage.

BE13: Physical damage to equipment directly affects operations.

BE14: Sudden temperature changes increase internal pipe stress.

BE15: Sole reliance on visual level checks increases the risk of error.

BE16: Inadequate visual inspection in empty tanks may lead to critical failures.

BE17: Malfunction of the vapor balancing system increases the risk of gas release.

BE18: Failure of pressure/vacuum valves may deform the tank.

BE19: Low quality gaskets lead to leakage and heat loss.

BE20: Non standard pipe materials cause deformation in the transfer line.

BE21: Using scraper systems without proper attachment may create discharge issues.

BE22: Overfilling the tank leads to overflow and contamination.

BE23: Cargo overflow following overfilling creates an environmental hazard.

BE24: Leakage in monitoring lines results in uncontrolled cargo loss.

BE25: Failure to drain the cargo line increases the risk of contamination.

BE26: Incorrect valve positioning may cause leakage or routing errors.

BE27: Operator misjudgment may affect the entire operation.

BE28: Accidental shutdown of systems leads to discharge interruption.

BE29: Planning errors disrupt the loading process.

BE30: Leakage in the thermal oil line causes heat loss and system malfunction.

BE31: Failure of the heating system at the pump head may halt discharging.

BE32: Frozen bitumen causes blockage and damage in the pump line.

BE33: Faulty decision making processes may lead to safety violations.

BE34: Failure to clean the pump filter causes flow obstruction.

BE35: Inadequate planning results in time loss and improper discharge.

BE36: Insufficient thermal oil reduces heating efficiency.

BE37: Gear pump failure directly impacts the discharge process.

BE38: Inadequate personnel may cause critical errors.

BE39: Lack of source monitoring creates gaps in the maintenance process.

BE40: Absence of a scheduled maintenance system leads to systematic failures.

BE41: Non compliance with PMS procedures results in irregular operations.

BE42: Lack of spare parts prevents renewal of critical equipment.

3.5.1.7 IE2 – Failures during voyage

These events represent failures arising from physical and environmental conditions that may occur while the vessel is underway. Such events typically emerge when cargo stability is compromised, temperature control is not maintained, or the safety of in tank dynamics cannot be ensured:

BE43: Inadequate insulation increases energy losses.

BE44: Lack of maintenance planning leads to long term system deterioration.

BE45: Insufficient heat transfer oil may disrupt the discharge process.

3.5.1.8 IE3 –Loading operation failures

These events refer to failures encountered during the loading process. Planning errors, technical deficiencies, or operator related shortcomings during this phase may lead to significant operational risks:

- BE46: Failure at connection points creates a leakage risk.
- BE47: Incorrect hose selection results in leakage and mechanical damage.
- BE48: Using a worn hose may cause rupture during discharge.
- BE49: Deficiencies in operational planning disrupt discharge sequence and efficiency.
- BE50: Errors in cargo handling may cause environmental damage.
- BE51: Malfunction of the cargo heating system increases product viscosity.
- BE52: General inefficiency in the heating system prolongs the transfer time.
- BE53: Poor heating performance reduces discharge rate.
- BE54: Loss of insulation in pipelines causes temperature drop.
- BE55: If the valve remains closed ahead of the pump, the system may clog.
- BE56: If the shore valve is closed, cargo transfer cannot occur.
- BE57: Temperature differences may lead to cargo stratification.
- BE58: Increased vapor pressure in the tank may pose structural risks.
- BE59: Uneven cargo distribution may affect vessel stability.
- BE60: Severe weather conditions make it difficult to control in tank temperatures.

3.5.1.9 IE4 – Discharge operation failures

This group specifically encompasses operational malfunctions encountered during the discharging process. The requirement to handle bitumen at elevated temperatures is directly associated with heating systems, pumping equipment, and operator interventions:

- BE61: Tank overfilling creates structural stress
- BE62: General failures in operational processes cause cascading disruptions
- BE63: Terminal related issues reduce discharge efficiency
- BE64: Incorrect initial flow rate disturbs system balance
- BE65: Excessively rapid discharge may lead to pressure increase in the system
- BE66: Lack of periodic maintenance contributes to a rise in system failures
- BE67: Operator performance deficiency leads to incorrect interventions

3.6 Logic Gates and Failure Relationships

The relationships in the fault tree are defined using "AND" and "OR" logic gates. "AND" gates indicate that all subordinate events must occur for the higher level event to take place, whereas "OR" gates signify that the occurrence of just one subordinate event is sufficient. This structure enables a clearer and more detailed analysis of the failure mechanisms.

3.7 Crisp Failure Probability

In this section, the Crisp Failure Probability (CFP) values of the 67 Basic Events (BEs), determined through the Intuitionistic Fuzzy Fault Tree Analysis (IFFTA) method based on expert evaluations, are analyzed. CFP represents a defuzzified numerical value that indicates the likelihood of each event contributing to overall system failure. It enables prioritization within fault tree analysis by providing a clear, uncertainty free probability metric.

BEs	CFPs	BEs	CFPs	BEs	CFPs
BE1	0,8053	BE24	0,4306	BE47	0,7025
BE2	0,4105	BE25	0,2279	BE48	0,6704
BE3	0,2689	BE26	0,5516	BE49	0,8266
BE4	0,2253	BE27	0,4626	BE50	0,5935
BE5	0,1032	BE28	0,2089	BE51	0,7098
BE6	0,1521	BE29	0,4648	BE52	0,6068
BE7	0,3642	BE30	0,4623	BE53	0,4742
BE8	0,4127	BE31	0,5858	BE54	0,2980
BE9	0,4991	BE32	0,3057	BE55	0,5775
BE10	0,4146	BE33	0,4509	BE56	0,6650
BE11	0,5074	BE34	0,2039	BE57	0,4451
BE12	0,4657	BE35	0,4473	BE58	0,6874
BE13	0,3812	BE36	0,5275	BE59	0,3149
BE14	0,4625	BE37	0,6340	BE60	0,6372
BE15	0,2124	BE38	0,7177	BE61	0,7345
BE16	0,2211	BE39	0,6285	BE62	0,5255
BE17	0,6279	BE40	0,6434	BE63	0,5654
BE18	0,6611	BE41	0,6599	BE64	0,1682
BE19	0,4886	BE42	0,5546	BE65	0,4015
BE20	0,1513	BE43	0,3643	BE66	0,6879
BE21	0,4821	BE44	0,5333	BE67	0,7143
BE22	0,6748	BE45	0,6792		
BE23	0,6261	BE46	0,6374		

Figure 3.2 : Calculated CFP values for each BE.

According to the results obtained, the events with the highest CFP values are BE49 (Operational planning error) and BE1 (Tank radar failure and overfilling). These events are evaluated under IE4 Discharge Operation Failures and IE1 Process Independent Operational Failures, respectively.

BE49 Operational planning error is a failure directly associated with the discharge operations process. It may occur due to incorrect flow planning prior to discharge, improper pump sequencing, inadequate hose configuration, or lack of coordination with terminal operations. Since maintaining operational flow continuity is critically important when handling high viscosity cargo such as bitumen, deficiencies in planning can trigger systemic failure. For this reason, BE49 exhibits a high CFP value; even a minor planning error can lead to cascading operational disruptions.

BE1 Tank radar failure and overfilling, although categorized as a process independent failure, has the potential to impact the entirety of both loading and discharging operations. In the event of a tank radar system malfunction, level measurements within the tank must rely on manual and less precise methods. This may lead to overflows, tank damage, or safety hazards for personnel particularly when dealing with high temperature fluids such as bitumen. The multifaceted nature of these risks explains why BE1 has a high CFP value.

On the other hand, the lowest CFP values were observed in BE5 (Tank cleaning related issues) and BE20 (Use of non standard pipeline materials). Although these events are classified under the category of process independent failures, their overall impact on the system has remained limited.

BE5 Tank cleaning related issues theoretically pose risks such as contamination from cargo residues, temperature control deviations, or reactive residue buildup. However, in bitumen transportation, tanks are typically used for a single cargo type, and the high temperature conditions between operations promote a self cleaning effect. As a result, the impact of this event on overall system failure is limited, which explains its low CFP value.

BE20 Use of non standard pipeline materials, although indicative of a systematic design flaw, poses a low contribution to operational risk due to the fact that such equipment selections are typically controlled and certified during the shipbuilding process. This type of failure is rarely encountered and is generally observed only in

older vessels or following improper modifications. The low frequency of occurrence has consequently positioned BE20 among the lowest CFP values.

In conclusion, as shown in Figure 3.2, the most critical events identified through the analysis are concentrated in systems with low error tolerance and high exposure to operator intervention particularly in areas dependent on human factors and real time decision making. In contrast, events that can be systematically managed or controlled at the design level have been assigned lower CFP values. These findings highlight the necessity of a cautious, procedural, and continuously monitored approach in high risk areas of bitumen tanker operations, such as planning, level control, and pump coordination.

3.8 Failure Probability (FP)

Within the scope of IFFTA, the obtained FP values represent the numerical probability that each basic event may contribute to overall system failure. These values were derived by defuzzifying the fuzzy data gathered from expert evaluations and are considered a reliable metric for the quantitative analysis of the fault tree. Figure 3.3 shows the calculated FP values for the BE's.

3.8.1 Events with the highest FP values

According to the analysis results, the highest FP values were identified as follows:

BE49 (Failure in operational planning) : 0,0429

BE1 (Tank radar failure and overfilling alarm failure) : 0,0369

BE49, categorized under discharge related failures (IE4), represents scenarios in which planning deficiencies may lead to cascading failures throughout the operation. In particular, incorrect organization of steps such as heating, pumping, flow rate management, and cargo transfer sequencing or communication breakdowns can result in operational interruptions and situations requiring emergency intervention. Planning related failures, when combined with parameters such as human factors, shift transitions, and inconsistencies between loading operations and written instructions, further increase the overall risk.

BEs	FPs	BEs	FPs	BEs	FPs
BE1	0,0369	BE24	0,0030	BE47	0,0187
BE2	0,0025	BE25	0,0003	BE48	0,0153
BE3	0,0006	BE26	0,0071	BE49	0,0429
BE4	0,0003	BE27	0,0038	BE50	0,0094
BE5	0,000019	BE28	0,0003	BE51	0,0196
BE6	0,0001	BE29	0,0039	BE52	0,0102
BE7	0,0017	BE30	0,0038	BE53	0,0042
BE8	0,0026	BE31	0,0089	BE54	0,0009
BE9	0,0050	BE32	0,0009	BE55	0,0084
BE10	0,0026	BE33	0,0035	BE56	0,0148
BE11	0,0053	BE34	0,0002	BE57	0,0033
BE12	0,0039	BE35	0,0034	BE58	0,0170
BE13	0,0020	BE36	0,0061	BE59	0,0010
BE14	0,0038	BE37	0,0121	BE60	0,0124
BE15	0,0003	BE38	0,0206	BE61	0,0230
BE16	0,0003	BE39	0,0117	BE62	0,0060
BE17	0,0117	BE40	0,0129	BE63	0,0078
BE18	0,0144	BE41	0,0143	BE64	0,0001
BE19	0,0046	BE42	0,0073	BE65	0,0024
BE20	0,0001	BE43	0,0017	BE66	0,0171
BE21	0,0044	BE44	0,0063	BE67	0,0202
BE22	0,0157	BE45	0,0161		
BE23	0,0115	BE46	0,0124		

Figure 3.3 : Failure probability calculations.

BE1, although not directly linked to the loading operation, poses a threat to overall system integrity and is classified under *Process Independent Operational Failures* (IE1). In the event of a radar system malfunction, incorrect measurement of tank fill levels may lead to overfilling. This can result not only in equipment damage but also in high impact consequences such as fire hazards and environmental pollution. The frequent susceptibility of radar systems to electronic failures, along with the occasional inability to compensate using manual measurements, are key factors contributing to the high FP value of this event.

Events with medium level FP values :

BE51 (Failure of the cargo heating system) – 0.0196

BE47 (Improper hose usage) – 0.0187

BE60 (Expose to heavy weather) – 0.0230

BE37 (Gear pump failure) – 0.0206

BE66 (Lack of regular maintenance) – 0.0171

These events are commonly observed during the discharge process and are directly related to equipment efficiency. Failures originating from the heating system or pumps can cause high viscosity bitumen to lose its fluidity, making it impossible to continue

the operation. Additionally, hose incompatibility and unexpectedly severe weather conditions are among the other contributing factors that elevate the FP values.

3.8.2 Events with the lowest FP values

The basic events with the lowest FP values identified in the analysis are as follows:

BE6 (Atmospheric humidity) – 0.0001

BE25 (Undrained cargo line) – 0.0003

BE3 (Failure due to different cargo type) – 0.0006

BE5 (Tank cleaning related) – 0.0002

BE20 (Substandard line materia) – 0.0003

These events are situations that, although unlikely to occur due to strict procedural oversight in bitumen tanker operations, must still be systematically considered in the analysis. For example, BE5 is associated with a low probability because bitumen is typically transported as a repeated, single type cargo, reducing the need for frequent tank cleaning. Similarly, BE20 represents an issue that is rarely encountered, thanks to shipbuilding standards and the control mechanisms enforced by classification societies.

3.9 MCS – Probability

MCS, refers to the smallest group of BEs that, when occurring together, are sufficient to cause system failure at the TE level in fault tree analysis. Each MCS represents a minimal combination of BEs that can trigger the TE. This method is of critical importance in system reliability analysis, as it helps identify the root causes of risk and determine the areas where preventive measures should be prioritized.

In the IFFTA model developed within the scope of this study, 67 Basic Events BEs representing potential risks during the cargo operations of bitumen tankers were identified, and the MCS formed by these events were analyzed along with their associated probability values. Figure 3.4 presents the MCS probabilities corresponding to the basic events.

MCS	Probability	MCS	Probability	MCS	Probability
BE1	3,69E-02	BE23	1,15E-02	BE45	1,61E-02
BE2	2,53E-03	BE24	2,98E-03	BE46	1,24E-02
BE3	6,14E-04	BE25	3,50E-04	BE47	1,97E-03
BE4	3,37E-04	BE26	7,12E-03	BE48	1,53E-02
BE5	1,86E-05	BE27	3,81E-03	BE49	4,29E-02
BE6	8,31E-05	BE28	2,59E-04	BE50	9,37E-03
BE7*BE8	4,38E-06	BE29	3,87E-03	BE51	1,96E-02
BE9	4,97E-03	BE30	3,80E-03	BE52	1,02E-02
BE10	2,62E-03	BE31	8,91E-03	BE53	4,15E-03
BE11	5,27E-03	BE32	9,45E-04	BE54	8,68E-04
BE12	3,90E-03	BE33	3,49E-03	BE55	8,45E-03
BE13	1,98E-03	BE34	2,38E-04	BE56	1,48E-02
BE14	3,81E-03	BE35	3,40E-03	BE57	3,34E-03
BE15	2,74E-04	BE36	6,05E-03	BE58	1,70E-02
BE16	3,15E-04	BE37	1,21E-02	BE59	1,04E-03
BE17	1,17E-02	BE38*BE39	2,42E-04	BE60	1,24E-02
BE18	1,44E-02	BE40	1,29E-02	BE61*BE62	1,37E-04
BE19	4,61E-03	BE41	1,43E-02	BE63	7,80E-03
BE20	8,16E-05	BE42	7,27E-03	BE64*BE65	2,82E-07
BE21	4,40E-03	BE43	1,70E-03	BE66	1,71E-02
BE22	1,57E-02	BE44	6,30E-03	BE67	2,02E-02

Figure 3.4 : MCS Probabilities of the BE's.

The event with the highest MCS probability is BE49 Failure in Operational Planning, with a value of 4.29E-02. This event falls under IE4 Discharge Operation Failures and highlights how planning errors in processes requiring the simultaneous monitoring and management of multiple technical variables such as temperature control, pump flow rate, and valve sequencing can lead to significant operational disruptions. The second highest value was calculated for BE1 Tank Radar Failure and Overfill, at 3.69E-02. This event is classified under IE1 Process Independent Operational Failures, and is associated with critical consequences such as the inability to maintain level control due to malfunctioning tank radar systems during loading. Overfilling may result in leaks or spillage, posing not only environmental risks but also serious threats to operational safety. Another notable event with a high MCS probability is BE22 Tank Overfilling, recorded at 1.57E-02. This event is directly related to BE1 and typically arises from limitations in automation systems, delayed alarm responses, or human error, leading to incorrect assessment of tank capacity during the loading process.

BE45 Lack of Thermal Oil also stands out with a probability value of 1.61E-02. This failure directly affects the operational efficiency of the heating systems and is categorized under IE4 Discharge Operation Failures. It influences the viscosity of the

cargo, potentially leading to discharge difficulties or even line blockages. Therefore, monitoring and timely replenishment of thermal oil is a critical preventive maintenance activity.

In addition, BE23 Cargo Spill Over the Ship's Side also exhibits a high probability value of $1.15E-02$ and is classified under IE3 Loading Operation Failures. Such a failure may occur particularly due to inadequate level control, communication breakdowns, or sudden interventions during operations.

The MCS with the lowest probability value was identified as the combination BE7*BE8 Oxygen Concentration and Spark Generation, with a calculated probability of $4.38E-06$. These events are connected via an AND gate, meaning that both must occur simultaneously to trigger a higher level failure. Due to the presence of static electricity prevention systems and atmospheric balancing mechanisms used in modern bitumen tankers, the simultaneous occurrence of these two events is highly unlikely. Another event with a low probability is BE6 Atmospheric Humidity, with a value of $8.31E-06$. During loading and discharging operations on bitumen tankers, the extremely high ambient temperatures reduce the operational impact of humidity, which is why this event is considered to present a very low level of risk.

BE5 Tank Cleaning-Related Issues, with a probability value of $1.86E-05$, is also among the events with the lowest MCS probabilities. This low risk is primarily attributed to the strict supervision of cleaning protocols carried out prior to operations and the widespread use of modern tank cleaning systems, which significantly reduce the likelihood of this failure mode leading to system level failure. Finally, BE20 Visual Ullage Check has been observed to carry a low probability value of $8.16E-05$. The increasing prevalence of automation systems has enabled the replacement of manual checks with precise level measurement sensors, thereby minimizing the impact of such human related errors on overall system performance.

3.10 The Fussell-Vesely Importance Measure

FVIM is a powerful tool used in fault tree analysis to evaluate the relative importance of each Basic Event (BE) with respect to system failure. As a fuzzified version of the classical Vesely approach, FVIM incorporates both intuitive expert assessments and mathematical probability distributions to enable risk prioritization. Through this

analysis, the most critical components for system safety can be identified, allowing for more effective decision making in areas such as maintenance, training, and resource allocation. Figure 3.5 presents the FVIM values calculated for each MCS.

MCS	FVIM	MCS	FVIM	MCS	FVIM
BE1	9,64E-02	BE23	3,02E-02	BE45	4,22E-02
BE2	6,63E-03	BE24	7,79E-03	BE46	3,24E-02
BE3	1,61E-03	BE25	9,15E-04	BE47	5,15E-03
BE4	8,81E-04	BE26	1,86E-02	BE48	3,99E-02
BE5	4,86E-05	BE27	9,97E-03	BE49	1,12E-01
BE6	2,17E-04	BE28	6,78E-04	BE50	2,45E-02
BE7*BE8	1,14E-05	BE29	1,01E-02	BE51	5,13E-02
BE9	1,30E-02	BE30	9,94E-03	BE52	2,67E-02
BE10	6,86E-03	BE31	2,33E-02	BE53	1,09E-02
BE11	1,38E-02	BE32	2,47E-03	BE54	2,27E-03
BE12	1,02E-02	BE33	9,13E-03	BE55	2,21E-02
BE13	5,17E-03	BE34	6,23E-04	BE56	3,86E-02
BE14	9,96E-03	BE35	8,88E-03	BE57	8,73E-03
BE15	7,18E-04	BE36	1,58E-02	BE58	4,45E-02
BE16	8,24E-04	BE37	3,17E-02	BE59	2,73E-03
BE17	3,05E-02	BE38*BE39	6,32E-04	BE60	3,24E-02
BE18	3,77E-02	BE40	3,37E-02	BE61*BE62	3,58E-04
BE19	1,21E-02	BE41	3,74E-02	BE63	2,04E-02
BE20	2,13E-04	BE42	1,90E-02	BE64*BE65	7,39E-07
BE21	1,15E-02	BE43	4,44E-03	BE66	4,46E-02
BE22	4,11E-02	BE44	1,65E-02	BE67	5,27E-02

Figure 3.5 : FVIM values.

According to the FVIM results, the Basic Event that contributes most significantly to system failure is BE49 Failure in Operational Planning, with an FVIM value of 1.12E-01. This event falls under IE4 Discharge Operation Failures and represents managerial weaknesses such as inadequate consideration of timing, coordination, thermal balance, and human factors during discharge operations. Such deficiencies can lead to serious consequences in terms of both operational continuity and environmental or structural safety. A lack of proper planning may not only cause direct operational failures but can also trigger a domino effect, leading to equipment wear, temperature deviations, and discharge line malfunctions. The second most critical Basic Event is BE1 Tank Radar Failure and Overfill, with an FVIM value of 9.64E-02. Classified under IE1 Process Independent Operational Failures, this event involves the malfunction of automatic level control systems, resulting in tanks exceeding their capacity limits. Since such failures pose a direct threat to environmental safety and vessel stability, they are considered high priority risks.

Similarly, the following events have also been identified as having high importance:

BE22 Tank Overfilling (FVIM = 4.11E-02): Loss of level control creates overflow risk, increasing the likelihood of environmental pollution and fire hazards.

BE45 Lack of Thermal Oil (FVIM = 4.22E-02): Directly affects the operation of the heating system, potentially causing the bitumen to solidify and disabling the pumping system.

BE11 Cargo Line Erosion (FVIM = 1.38E-02): Prolonged exposure to high temperatures may lead to structural fatigue and an increased risk of leakage.

BE9 Use of Inappropriate Materials (FVIM = 1.30E-02): Equipment incompatible with high viscosity fluids can result in serious malfunctions.

BE14 Thermal Shock (FVIM = 9.96E-03): Material deformation caused by sudden temperature changes poses a threat to system integrity.

The high FVIM values of these basic events indicate that particular attention must be given to these areas in terms of both equipment reliability and operational planning.

The event combination BE7*BE8 Oxygen Concentration & Sparkling recorded the lowest FVIM value, at 1.14E-05. Due to the presence of advanced safety measures and static electricity prevention systems, this event pair is largely mitigated, resulting in a limited contribution to system failure.

Other basic events with low importance are as follows:

BE5 Tank Cleaning Related Issues (FVIM = 4.86E-05): The strict implementation of standard operating procedures effectively prevents such failures.

BE6 Atmospheric Humidity (FVIM = 2.17E-04): High quality insulation and tank sealing systems minimize the impact of this parameter on system failure.

BE20 Visual Ullage Check (FVIM = 2.13E-04): In operations supported by automation systems, the relevance of manual measurement errors is significantly reduced.

BE21 Use of Scraper System Without Proper Installation (FVIM = 1.15E-02): A simple operator error that can be easily prevented through monitoring and adherence to procedures.

4. RESULTS AND DISCUSSIONS

This study aimed to analyze the risk profile of bitumen tanker operations using the IFFTA method, with the objective of identifying the weakest links in the system and developing preventive strategies. In particular, the technical, environmental, and operational challenges encountered during the transportation of bitumen, a high viscosity cargo with significant temperature sensitivity were detailed within the fault tree model and quantitatively evaluated.

According to the analysis results, the most significant contributors to system failure were identified as BE49 Failure in Operational Planning and BE1 Tank Radar Failure and Overfill. With FVIM values calculated as 0.112 and 0.0964 respectively, these two events hold critical importance in terms of both failure probability and impact severity. BE49 was found to originate primarily from deficiencies in timing, equipment coordination, and operator intervention during discharge operations. This failure not only leads to efficiency losses but also creates a basis for cascading system malfunctions, accompanied by environmental and safety risks. Similarly, BE1, which represents the malfunction of the tank radar system, can result in overfilling due to incorrect level detection posing serious threats to both structural integrity and the environment.

In this context, the following recommendations have been developed to enhance system safety and prevent the occurrence of these critical failures:

Review of Operational Planning: Predischarge procedures should be scenario based and supported by step by step traceable checklists. Deficiencies in planning not only disrupt workflow but also diminish the effectiveness of emergency response capabilities.

Redundancy in Automation Systems: The most effective measure against BE1 is not only the regular testing and maintenance of tank radar systems but also the revision of manual measurement methods. Additionally, it is recommended to integrate alternative warning systems such as secondary alarms or flow rate analysis that can be activated in the event of radar sensor failure.

Performance Monitoring of Heating and Thermal Systems: Events such as BE45 Lack of Thermal Oil (FVIM = 0.0422) and BE51 Heating System Failure (FVIM = 0.0513) may lead to operational failure due to the inability to maintain cargo viscosity. To ensure continuous monitoring of these systems, the implementation of digital sensor based thermal profile mapping is recommended, and periodic performance testing should be mandated.

Emergency Protocols for High Risk Failures: Events such as BE22 Tank Overfilling and BE67 Operator Performance Deficiency fall under both technical and human related failure categories, requiring dual mode intervention. Routine implementation of training programs, simulations, and crisis scenarios at the operator level will be effective in mitigating these risks.

Making Isolated Risks Visible: Events with low FVIM values, such as BE5: Tank Cleaning Related Issues may appear to have limited direct impact on system failure; however, they can become critical when combined with other events. Therefore, it is essential to establish minimum control checkpoints even for low probability failures.

This analysis is not merely a tool for identifying the current state, but also serves as a foundation for developing forward looking preventive maintenance strategies. Through FVIM based prioritization, ship operators gain the opportunity to allocate limited resources toward the areas posing the highest risk. Furthermore, comparisons using MCS values revealed that certain basic events are involved in multiple failure paths, thereby enabling the visualization of critical nodes within the system.

In conclusion, this thesis presents a risk assessment model designed to contribute to the safer, more sustainable, and predictable execution of bitumen tanker operations. Validated through field experience, the model can serve as a guiding tool for companies operating in the maritime industry, operational managers, and classification societies supporting both strategic decision making and operational planning processes.

This thesis has presented a highly specialized and methodologically advanced risk assessment framework for bitumen tanker operations, a sector that poses distinct operational and safety challenges due to the chemical and physical nature of its cargo. Despite the criticality of bitumen transportation in global infrastructure development, scholarly attention to its operational risk profile remains limited. By integrating IFFTA

into the analytical framework, this study offers an original contribution that bridges the gap between traditional deterministic models and the fuzzy, complex realities of maritime operations involving thermally sensitive cargo.

The methodological innovation of this study lies in its rigorous treatment of uncertainty and subjectivity in risk assessment. IFFTA, by incorporating both membership and non membership functions along with hesitation margins, allows for a more comprehensive modeling of expert judgment under uncertainty. This is particularly significant in maritime contexts, where standardized incident data may be sparse or incomplete, and experiential knowledge is often the primary source of insight. The use of 67 distinct basic events evaluated through expert input weighted by operational background, academic qualification, and sea/shore experience provided a granular risk taxonomy. The structured conversion of linguistic variables into intuitionistic fuzzy numbers further ensured the scientific consistency of the model.

Academically, this thesis expands the application horizon of fuzzy logic within maritime risk research, offering a replicable model that can be extended to other niche operations, such as LNG bunkering, offshore supply logistics, or polar navigation. It reinforces the notion that the intersection of engineering, human systems, and environmental variables cannot be effectively modeled using purely probabilistic or binary methodologies. In doing so, it contributes to the evolving literature on hybrid risk modeling and strengthens the case for integrating fuzzy inference systems into maritime safety frameworks.

The empirical results also yield several critical insights into the nature of operational vulnerability in bitumen tanker transport. Notably, the highest ranked risk contributors were not isolated to technical failure modes, but were predominantly associated with human performance and organizational shortcomings. Inadequate training, incomplete operational planning, and deviation from procedural norms emerged as significant precursors to cascading failures. These findings echo the conclusions of HRO theory, which emphasizes that systemic failures often originate from latent human and organizational deficiencies rather than frontline equipment breakdowns alone.

Moreover, structural limitations such as thermal insulation degradation, insufficient heating system redundancy, and temperature control feedback lag were identified as exacerbating factors that compromise the thermal integrity of bitumen cargoes. These

latent design vulnerabilities, although categorized as process independent in the fault tree structure, interact dynamically with real time operations, particularly during long voyages or in cold climates. The thesis, therefore, calls for the revision of current design notations and class society requirements to integrate adaptive criteria that reflect not only structural resilience but also functional performance under variable environmental stressors.

One of the most conceptually significant findings of the study is the misalignment between formal regulatory compliance and actual operational behavior. While the IMO, SOLAS, and IMDG frameworks offer comprehensive regulatory scaffolds, the field data analyzed here underscore a pronounced implementation gap. Factors such as commercial time pressures, crew fatigue, and logistical complexity often lead to compromised adherence, revealing the limitations of prescriptive regulation in dynamic operational settings. This suggests the need for a shift toward performance based regulation complemented by continuous monitoring and adaptive risk management mechanisms.

The study's use of the FVIM and MCS further enhanced the diagnostic depth of the analysis. These tools allowed for the prioritization of high impact scenarios and provided stakeholders with a roadmap for targeted intervention. The combination of expert-based fuzzification with statistical importance ranking represents a compelling methodological synergy, offering both qualitative sensitivity and quantitative rigor. The study also lays the groundwork for future validation studies using empirical incident datasets or simulation-based risk modeling platforms.

From a broader systems engineering perspective, the research advocates for the institutionalization of hybrid risk assessment tools within SMS of shipping companies, particularly those operating in specialized segments such as bitumen transport. The model developed in this thesis is not only suitable for academic replication but also holds promise as a decision support mechanism for ship managers, classification societies, and port authorities.

In conclusion, the safe transport of bitumen requires a nuanced understanding of multi-level risk interactions, spanning technical, human, procedural, and regulatory domains. This study demonstrates that the integration of fuzzy logic into structured risk modeling provides a superior analytical lens to capture these interactions. The IFFTA

based framework, validated through expert engagement and case specific modeling, offers both theoretical depth and practical utility. Its application can meaningfully enhance risk visibility, decision-making precision, and safety performance in bitumen tanker operations serving as a benchmark for future research and industrial implementation alike.





5. CONCLUSIONS AND RECOMMENDATIONS

This thesis has presented an advanced and interdisciplinary framework for understanding and mitigating the risks associated with bitumen tanker operations through the application of IFFTA. By incorporating both qualitative expert insight and quantitative fuzzy logic tools, the study has addressed the complex, high uncertainty environment of maritime bitumen transport in a methodologically rigorous manner.

The empirical results of the study have highlighted the predominance of human and procedural failures over technical malfunctions in determining operational risk. These insights not only emphasize the need for structured training programs and crew competency development but also call for a cultural shift towards proactive risk management and institutional learning within shipping companies. The importance of integrating continuous monitoring systems and digital diagnostics further underlines the role of technological innovation in risk mitigation.

Structurally, the research also exposes design vulnerabilities that, although often overlooked, have significant operational implications particularly under varying climatic and voyage conditions. These findings contribute to the argument for revising current vessel construction and classification norms to incorporate performance-based design standards, especially for tankers dealing with heat-sensitive cargo.

The integration of FVIM and MCS within the IFFTA methodology offers an advanced decision-support mechanism, allowing maritime stakeholders to allocate limited resources more strategically by targeting high-impact failure nodes. This capability enhances not only operational planning but also regulatory foresight and port-state control preparation. Furthermore, the identification of mismatches between regulatory frameworks and onboard realities suggests that maritime governance must evolve towards adaptive, data-driven, and feedback-oriented systems.

From an academic perspective, this thesis enriches the limited body of research on bitumen tanker risk assessment by bridging systems engineering, fuzzy mathematics, and maritime operations. It lays a foundational methodology that is replicable and

scalable across other high risk marine cargo domains, including liquefied gases, hazardous chemicals, and Arctic shipping.

Ultimately, the safe and sustainable transport of bitumen demands a paradigm shift in maritime safety philosophy one that transcends checklists and prescriptive codes and instead embraces dynamic, real-time, and holistic risk governance. The IFFTA model developed herein offers both a theoretical contribution to maritime risk literature and a practical tool for industry implementation, aiming to elevate safety outcomes, compliance efficiency, and operational resilience in the specialized domain of bitumen transport.

Building upon the findings and methodological contributions of this thesis, future research can explore several promising directions. First, the integration of dynamic simulation techniques, such as Monte Carlo analysis or Bayesian networks, can further enhance the predictive accuracy of risk modeling in bitumen tanker operations. Second, expanding the expert dataset through the inclusion of international practitioners, classification societies, and port state control authorities would enhance the generalizability of the IFFTA model across varied regulatory and operational contexts. Third, longitudinal studies that incorporate real-world incident and near-miss data can be conducted to validate and calibrate the fuzzy risk parameters derived in this study. Additionally, the application of this model to other high-risk maritime domains—such as ammonia carriers, LNG bunkering vessels, or polar-class oil tankers—may uncover domain-specific risk patterns and allow for the refinement of hybrid risk assessment methodologies.

Furthermore, future research should consider incorporating Human Reliability Analysis (HRA) techniques—such as the Technique for Human Error Rate Prediction (THERP) or Cognitive Reliability and Error Analysis Method (CREAM)—to quantify the influence of cognitive and behavioral factors on failure likelihoods in bitumen tanker operations. Coupling HRA with IFFTA could create a more comprehensive socio-technical risk model. In addition, the development of real-time, dynamic risk assessment platforms that integrate live vessel data, sensor feedback, and environmental variables can enable predictive safety analytics. Such systems could be utilized for both onboard decision-making and shore-based safety monitoring, providing an avenue for the maritime industry to transition from reactive safety compliance to proactive risk governance.

REFERENCES

- Bauquis, P.-R.** (1998, September). What future for extra heavy oil and bitumen: The Orinoco case. In **17th Congress of the World Energy Council**, Houston, USA.
- Bitumen and heavy crudes: The energy security problem solved?** (2006). **Oil and Energy Trends**, 31, 3–6. <https://doi.org/10.1111/j.1744-7992.2006.310603.x>
- Boffetta, P., Burstyn, I., Partanen, T., Colin, D., & Heikkilä, P.** (2003). Cancer mortality among European asphalt workers: An international epidemiological study. I. Results of the analysis based on job titles. **American Journal of Industrial Medicine**, 43(1), 18–27.
- Clark, C. R., Burnett, D. M., Parker, C. M., Arp, E. W., Swanson, M. S., Minsavage, G. D., ... & Stewart, C. W.** (2011). Asphalt fume dermal carcinogenicity potential: I. dermal carcinogenicity evaluation of asphalt (bitumen) fume condensates. *Regulatory Toxicology and Pharmacology*, 61(1), 9-16.
- De Sanctis, M. C., Ammannito, E., McSween, H. Y., Raponi, A., Marchi, S., Capaccioni, F., ... & Russell, C. T.** (2017). Localized aliphatic organic material on the surface of Ceres. **Science**, 355(6326), 719–722.
- Eurobitume.** (2022). **Annual Bitumen Use Report**.
- Eurobitume & Asphalt Institute.** (2024). *The bitumen industry: A global perspective* (4th ed.). Brussels, Belgium: Eurobitume; Lexington, KY: Asphalt Institute. Retrieved from <https://eurobitume.eu/wp-content/uploads/2024/06/The-Bitumen-Industry-A-Global-Perspective-IS-230-4th-edition.pdf>.
- Fortune Business Insights.** (2025). Bitumen market: Global industry trends and forecast to 2029. Retrieved June 30, 2025 from <https://www.fortunebusinessinsights.com/bitumen-market-104300>
- IMARC Group.** (2024). **Bitumen market: Global industry trends, share, size, growth, opportunity and forecast 2024–2032**.
- International Maritime Organization.** (2022). *International Convention for the Prevention of Pollution from Ships (MARPOL)*.
- International Maritime Organization.** (2020). *International code for the construction and equipment of ships carrying dangerous chemicals in bulk (IBC Code)*. London: IMO Publishing.
- Kriech, A. J., & Osborn, L. V.** (2014). Review and implications of IARC monograph 103 outcomes for the asphalt pavement industry. *Road materials and pavement design*, 15(2), 406-419.

- Kumar, S., & Singh, M.** (2019). Intuitionistic fuzzy fault tree analysis in complex systems. *Journal of Intelligent & Fuzzy Systems*, 37(6), 7655–7666. <https://doi.org/10.3233/JIFS-179328>
- Liu, Y., & Wang, Z.** (2022). Linguistic risk evaluation in intuitionistic fuzzy environments. *Applied Soft Computing*, 116, 108392. <https://doi.org/10.1016/j.asoc.2021.108392>
- Muratova, A., Hübner, T., Narula, N., Wand, H., Turkovskaya, O., Kusch, P., Jahn, R., & Merbach, W.** (2003). Rhizosphere microflora of plants used for the phytoremediation of bitumen-contaminated soil. *Microbiological Research*, 158(2), 151–161.
- Lee, W. S., Grosh, D. L., Tillman, F. A., & Lie, C. H.** (2009). Fault tree analysis, methods, and applications a review. *IEEE transactions on reliability*, 34(3), 194-203.
- Loomis, D., Guyton, K. Z., Grosse, Y., Lauby-Secretan, B., El Ghissassi, F., Bouvard, V., ... & Straif, K.** (2018). Identifying occupational carcinogens: An update from the IARC Monographs. *Occupational and Environmental Medicine*, 75(8), 593–603.
- Nciri, N., Tazerout, M., Khabbazi, A., & Hadrich, F.** (2014). Chemical characterization of gilsonite bitumen. *Journal of Petroleum & Environmental Biotechnology*, 5(5), 1. <https://rahaoil.com/gilsonite/>
- Read, J., & Whiteoak, D.** (2003). *The Shell Bitumen Handbook*. Thomas Telford.
- Statista Research Department.** (2024). Ocean shipping – Statistics & facts. *Statista*. <https://www.statista.com/topics/1728/oceanshipping/#topicOverview>
- Tüpraş.** (2022–2024). *Entegre faaliyet raporu*.
- Türkiye İstatistik Kurumu (TÜİK).** (2023). *Ham petrol ve petrol ürünleri ithalat/ihracat verileri*.
- U.S. Energy Information Administration (EIA).** (2021). *Petroleum and other liquids – Asphalt and road oil movements*.
- Wang, Y., Liu, H., & Zhang, M.** (2015). Weighting expert judgment in fuzzy risk assessment models. *Expert Systems with Applications*, 42(7), 3387–3395. <https://doi.org/10.1016/j.eswa.2014.11.033>
- Xie, M., Ng, S. H., & Goh, T. N.** (2017). *Statistical methods for risk and reliability analysis*. Springer. <https://doi.org/10.1007/978-3-319-53850-1>
- Zhang, X., Wang, J., & Li, Y.** (2020). System failure analysis using fuzzy fault tree and expert opinion. *Safety Science*, 124, 104580. <https://doi.org/10.1016/j.ssci.2019.104580>

CURRICULUM VITAE

Name-Surname : Batur Alp ÖZDEMİR

B.Sc.:

- **Bachelor** : 2013, İstanbul Teknik Üniversitesi, Denizcilik Fakültesi, Deniz Ulaştırma ve İşletme Mühendisliği

Professional Experience and Rewards:

- 2023 – ... : Ditaş Tanker, Kalite ve Emniyet Enspektörü
- 2023 – 2023 : Ditaş Tanker, Oceangoing Master
- 2021 – 2022 : Yasa Tanker – Yasa Holding S.A., Oceangoing Master

Publications, Presentations, and Patents Derived from the Master's Thesis

- **Özdemir, B. A., & Şenol, Y. E.** (2025). Risk assessment of bitumen tanker discharge operations using intuitionistic fuzzy fault tree analysis. In S. Can (Ed.), *5th BİLSEL International Turabdin Scientific Researches and Innovation Congress Book* (pp. 33–43). BILSEL Publishing.